

# Using Dynamic Simulation to Teach Physics in a Real-World Context

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## Abstract

*Dynamic simulation has great potential as a tool for teaching physics and science in general. This paper describes a family of simulators that have been developed to teach several topics in physics including circular motion, collisions, energy storage, and heat flow. These simulators provide students with laboratories for experimenting with the phenomena in the context of real-world situations such as driving, home energy conservation, and sports. The simulators were designed to serve as companions to a curriculum called Active Physics (AP) which was created with NSF support to make the subject more appealing and understandable to the majority of high school students who otherwise do not study physics. The paper contrasts dynamic simulation and traditional approaches to teaching physics. It also discusses the value of simulators with "user-friendly" interfaces compared to using System Dynamics models alone. The paper describes how each phenomenon was modeled and presents interfaces for each simulator.*

Key Words: K-12 education, science, physics, simulators

## Introduction

This paper describes a family of simulators that have been developed to teach several topics in physics including circular motion, collisions, energy storage, and heat flow. The simulators were designed to serve as companions to a curriculum called Active Physics (AP). AP emphasizes the connection with everyday life and organizes physics into six units with titles such as Transportation (mechanics), Home (heat flow and electricity), Sports (mechanics), and Communications (wave motion). Though Active Physics influenced the selection of topics and pedagogical approach, these simulators can also be used independently with other curricula.

The paper describes how each phenomenon was modeled as a dynamic system of elements working together to produce the behavior students are trying to understand. Interfaces are also presented for each simulator to illustrate the kind of parameters students can manipulate to do experiments and the information they receive to interpret simulation results. Other design features such as built-in tutorials are also shown. The paper concludes with a discussion of lessons from early field-testing and review by teachers, pedagogical issues involved in using simulators such as the degree of "scaffolding" (structuring interactions) that is desirable, and next steps and future plans for further developing the simulators.

## Dynamic Simulation vs. "Traditional" Approaches

Many of the phenomena physics students learn about are dynamic in nature. However, traditional methods of teaching have been static and do not help students develop intuition about the dynamic aspects. Textbooks emphasize using formulae to get particular answers such as the amount of centripetal force required to keep a car on the road when it is going at a velocity  $v$  on a curve of radius  $r$ . Students may learn how to get the answer, but not really understand the dynamics of a skid, how the propensity to skid is affected by ice or rain on the road, and how the driver's reaction to a skid can make things worse. (This intuition has important real-world implications for inexperienced teen-aged drivers.) Laboratory experiments done in traditional courses might give students a better sense of the inherent dynamics, but are typically done with artifacts such as carts on turntables or rolling down ramps that have limited meaning for students. Taking students out in cars on icy roads poses obvious problems.

Computers, multimedia, and the world-wide-web have provided some new tools for illustrating and explaining these dynamic phenomena. Many of the animations and videos that are available serve as demonstrations, but don't allow students to manipulate and experiment with them. It is this engagement that is essential for really understanding scientific concepts rather than just memorizing formulae. One new curriculum, Constructing Physics Understanding (CPU) overcomes this limitation by putting lab experiments on the computer. This is a major advantage, freeing students and teachers from being limited by available physical artifacts and giving them additional tools for visualization, but still has the limitation of working within the somewhat abstract confines of the laboratory bench. Interactive Physics is another simulation-based curriculum that puts the lab bench on the computer.

As indicated earlier, Active Physics attempts to overcome the abstractness of the traditional approach by recasting physics in terms of activities familiar to students. It gets students to think about these phenomena based on personal experience, but has laboratory activities that look more like the traditional ones. Making the connection back to the real world is a challenge. The simulators described in this paper attempt to "close the loop", as shown in Figure 1, by providing a virtual laboratory using real-world examples, but without the attendant risks and difficulties.

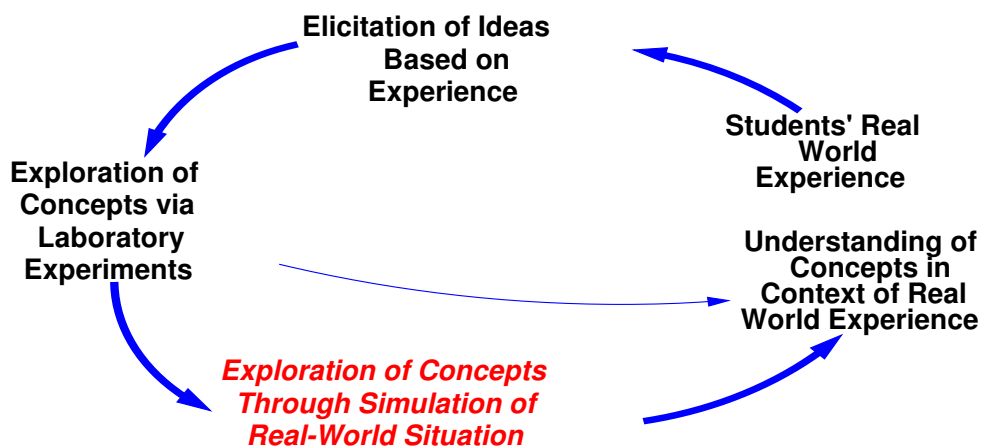


Figure 1: Relationship of Simulators to Active Physics Curriculum

## **Simulators vs. System Dynamics Models**

There have been a number of applications of System Dynamics to physics and to science in general. One of the most extensive projects that provides models to teachers is that of Mary Ellen Verona and her colleagues at the Maryland Virtual High School. This project provides models of biological and physical processes using STELLA. The Shodor Foundation makes available a similar range of simple STELLA models on environmental topics and other types of models on biological topics such as cardiovascular function and galaxy formation. Diana Fisher and Ron Zaraza and their colleagues at the CC-STADUS program extend the availability of STELLA models into the social sciences. The Systems Thinking and Curriculum Innovation Network (STACIN) helped teachers develop a number of models for classroom use.

These models are a valuable resource for teachers motivated to learn System Dynamics. But what about the much larger group of teachers simply interested in doing a better job of teaching physics? Mandinach and Cline suggest a set of interrelated factors that serve as barriers to adopting systems thinking and modeling that include teachers having too little time, training, and access to expert knowledge. Expecting teachers to learn a new discipline to access new ways of teaching may be unfair, especially if it is difficult for them to see the benefits until after they have invested the necessary time.

Pre-existing models by themselves can have other pitfalls. Work by Roberts and Barowy suggests that using models in too open-ended a fashion can lead to having students flail around and waste energy without really learning. On the other hand, highly structured use can lead to teacher-centered patterns that hinder the kinds of student exploration that simulation is designed to promote. They describe a potentially more effective process of guided inquiry in which students are first engaged in learning by helping to develop goals and then using a model to test hypotheses. These findings suggest that simply making models available may not be helpful and that models must be used carefully.

The simulators described in this paper present models packaged to overcome some of these obstacles. The strength of the approach is that it permits real inquiry and exploration while allowing teachers greater comfort than they might have with building models from scratch. The simulators can also be structured to guide the way they are used and to promote patterns of use that are neither too open-ended nor too restrictive. The simulators contain models, but are packaged to be about physics rather than about modeling per se. This should appeal to teachers who are unfamiliar with modeling, pressed to teach what they already have to, and unwilling to learn a new discipline without a way to relate it to what they already have to teach. These simulators can demonstrate the value of simulation and modeling and get teachers interested.

These simulators were developed under the sponsorship of the Vermont Institute of Science, Mathematics, and Technology with funding from the National Science Foundation. Vensim provided both simulation modeling and interface capabilities.

## Travel Around a Curve: Simulating Circular Motion with a Driving Example

Circular motion is not thought of as a dynamic problem as readily perhaps as a spring-mass-damper or hydraulic system. As indicated earlier, the traditional emphasis has been on using formulae to calculate a velocity or radius at which a car will go off a road. The Transportation unit in the Active Physics curriculum gets students to think about this phenomenon based on their own experience with driving and running tracks and then do experiments with motorized cars and "lazy Susan" turntables. How does what they learn in the lab relate back to driving? How can it be presented as a dynamic problem?

If a car is going at a prudent speed, friction between the tires and the road, possibly assisted by banking of the road, will keep the car following the desired curved path with no radial movement away from the center. Not very dynamic. However, if a car enters a curve at an initial velocity that is too great for the radius and/or road conditions, a skid will begin to occur and the dynamic nature of the problem becomes obvious. In terms of the relationships shown in Figure 2, the Centripetal Acceleration Required (equal to velocity squared divided by radius) will exceed the Centripetal Acceleration Due to Friction and Banking and there will be a positive Net Radial acceleration away from the center of the curve. Though the car will continue moving forward (at a reduced speed), a component of its overall movement will be a Radial Velocity that takes it away from the center and increases the Actual Radius of the Turn.

This is a scary situation, but the good news is that, as the car skids away from the road and the Actual Radius of the Turn increases, the Centripetal Acceleration Required is reduced (since Radius is in the denominator). Net Radial Acceleration also decreases toward zero as a result and the car eventually settles into equilibrium. At this point, the Actual Radius of the Turn is large enough and Forward Velocity slow enough that the Centripetal Acceleration Due to Friction and Banking Effect are sufficient to allow the tires to "grab" the road and stop the skid.

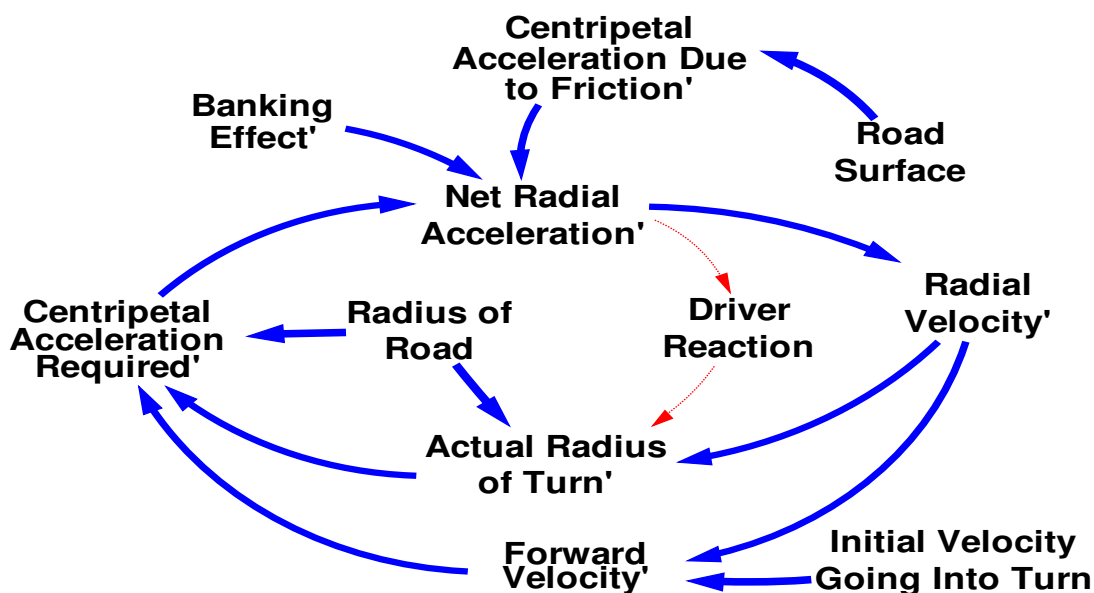


Figure 2: Structure of the Model Underlying the Travel Around a Curve Simulator

Telling students about these dynamics is one thing, but enabling them to experiment with different combinations of parameters is what the simulator is all about. Figure 3 shows an input screen that students use to set up experiments. They control the velocity of the car entering the curve, the radius, road conditions, and the angle of banking. "Pop-up" boxes such as the one shown for Velocity, suggest experiments to help students understand the role of the different parameters in causing or preventing a skid and discourage them from changing too many things at once.

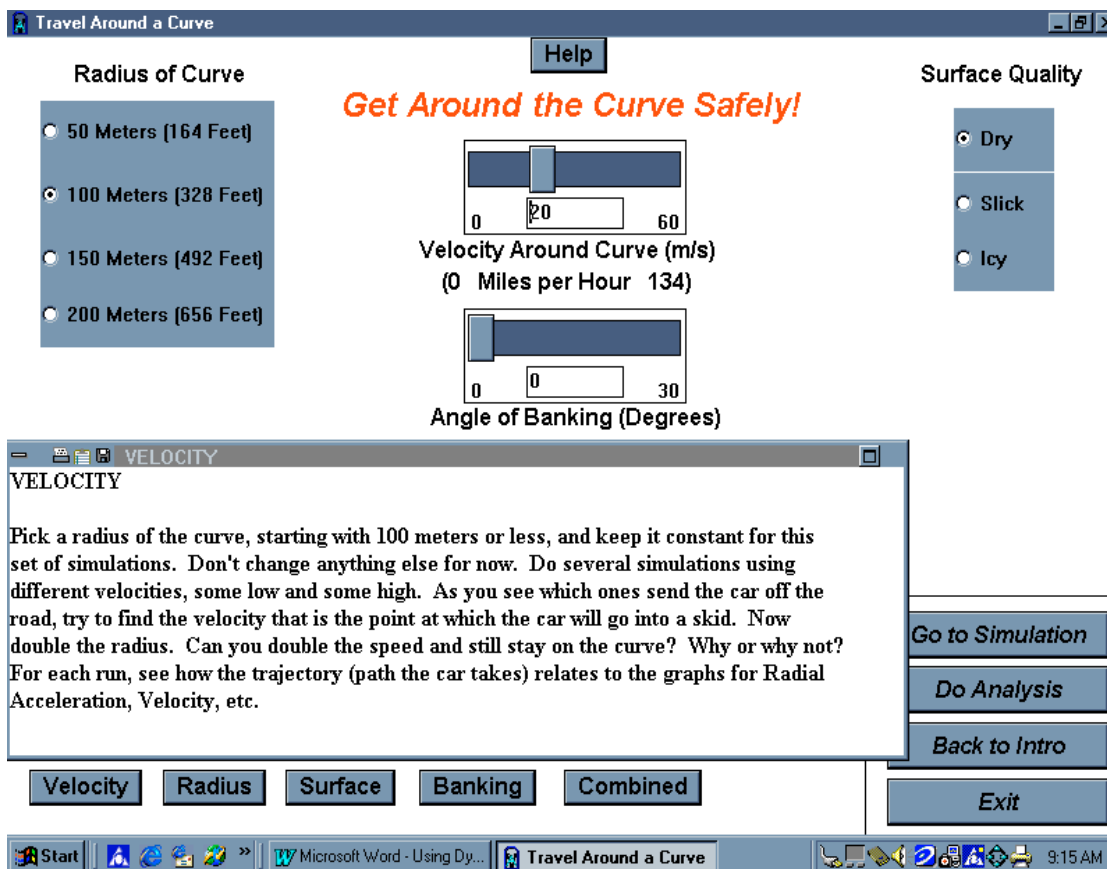


Figure 3: Input Screen for Setting Up Experiments

As students do experiments, they need information on the trajectory the car will follow under each set of conditions and other variables such as the Net Radial Acceleration and Actual Radius of the Turn as they change over time. Figure 4 shows a typical output screen with this information displayed for an experiment at which the car attempted to negotiate a curve with a radius of 100 meters going at a velocity of 40 meters per second. As shown on the graph, the car goes into a skid that takes it off the road. It follows a trajectory (red line) with a radius that grows until it is large enough for the car to reach an equilibrium radius and forward velocity. This is confirmed by the graph in the lower right-hand corner that shows the Net Radial Acceleration (in blue) to be greatest as the car enters the turn. It decreases to zero over the next few seconds as the Actual Radius of the Turn (in red) increases to its equilibrium value of 125 meters and Forward Velocity drops. The picture in the upper right-hand corner is controlled by the simulation results and provides information in a more dramatic form. It shows the student

that, at this velocity, the car would have gone off the road and into the trees. Providing information in these different forms increases the value of the simulators for students with different learning styles.

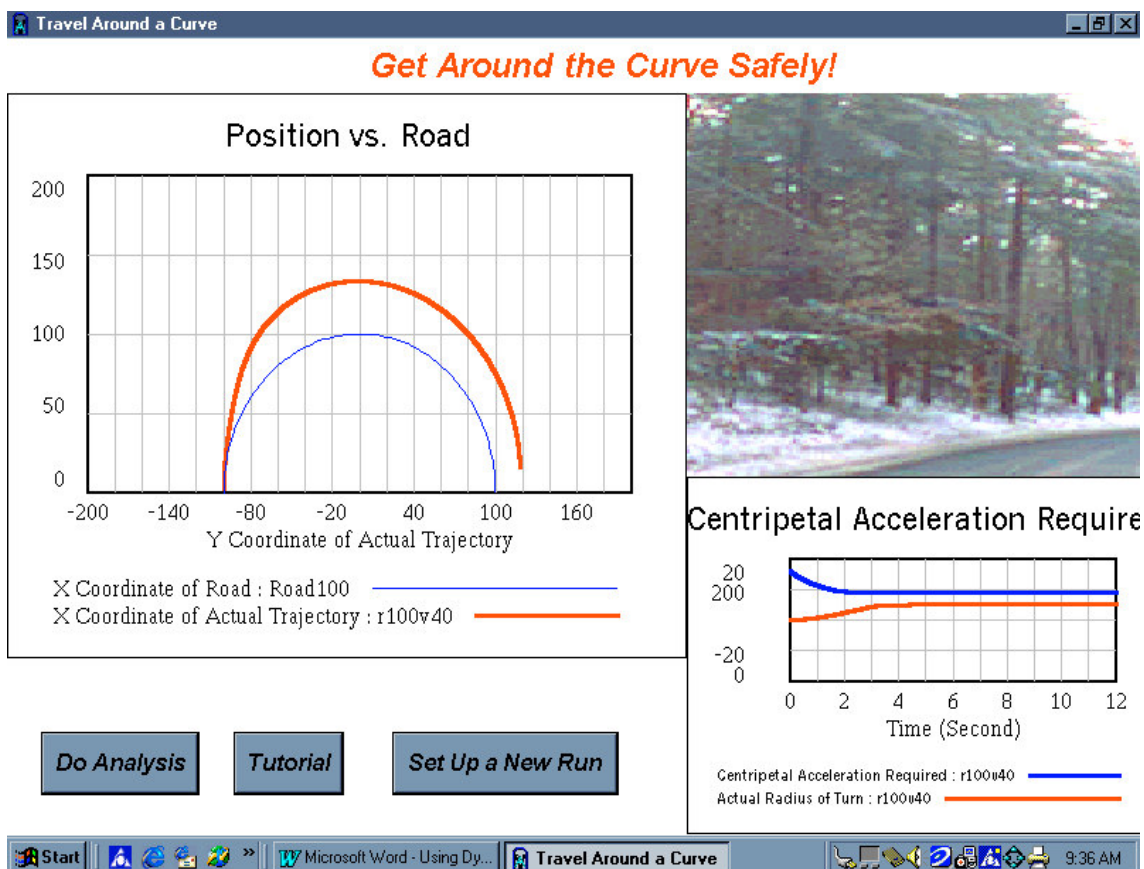


Figure 4: Results of Simulation Where Skid Occurs

The first experiments done by students are ones in which they choose a set of parameters and watch the simulation play out. Once they master the interrelationships among velocity, radius, road surface, and banking, students have the opportunity to "improve" on the skid by steering and braking, much as a driver would do in a real-world skid. This is reflected by the additional feedback loop shown in Figure 2 through Driver Reaction. Figure 5 shows the results of trying to steer sharply back toward the road to compensate for the skid. The velocity and radius are the same 40 meters per second and 100 meters as in the previous simulation. The (red) line that goes further away from the road is the trajectory produced by steering, a worse result than traveling at the same speed without steering (in green).

Why did this happen? Figure 6 shows a Tutorial students can access that explains the effect of steering. Throwing the wheel sharply back toward the road effectively reduces the radius of the turn and increases the Centripetal Acceleration Required. Net Radial Acceleration, which was decreasing as the skid moved the car toward an equilibrium radius and velocity, suddenly jumps as steering is applied. The result is that it takes longer to reach equilibrium and the trajectory takes the car further from the road.

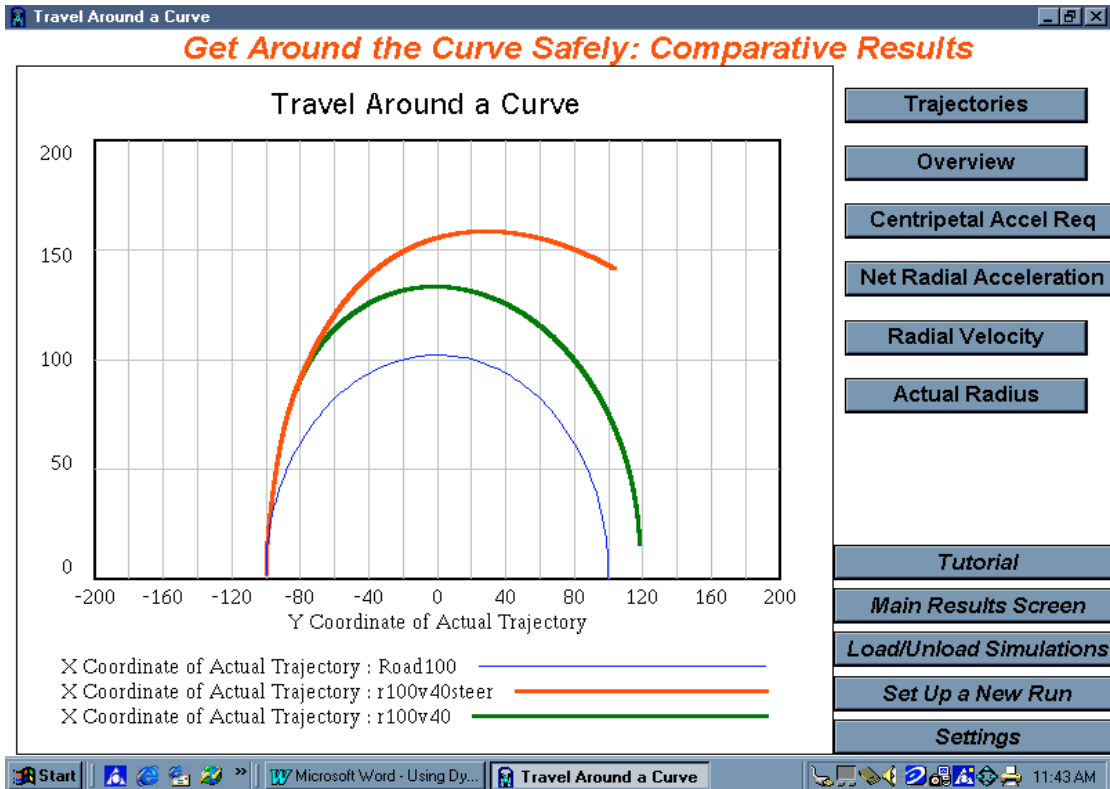


Figure 5: Comparison of Trajectories with and Without Steering

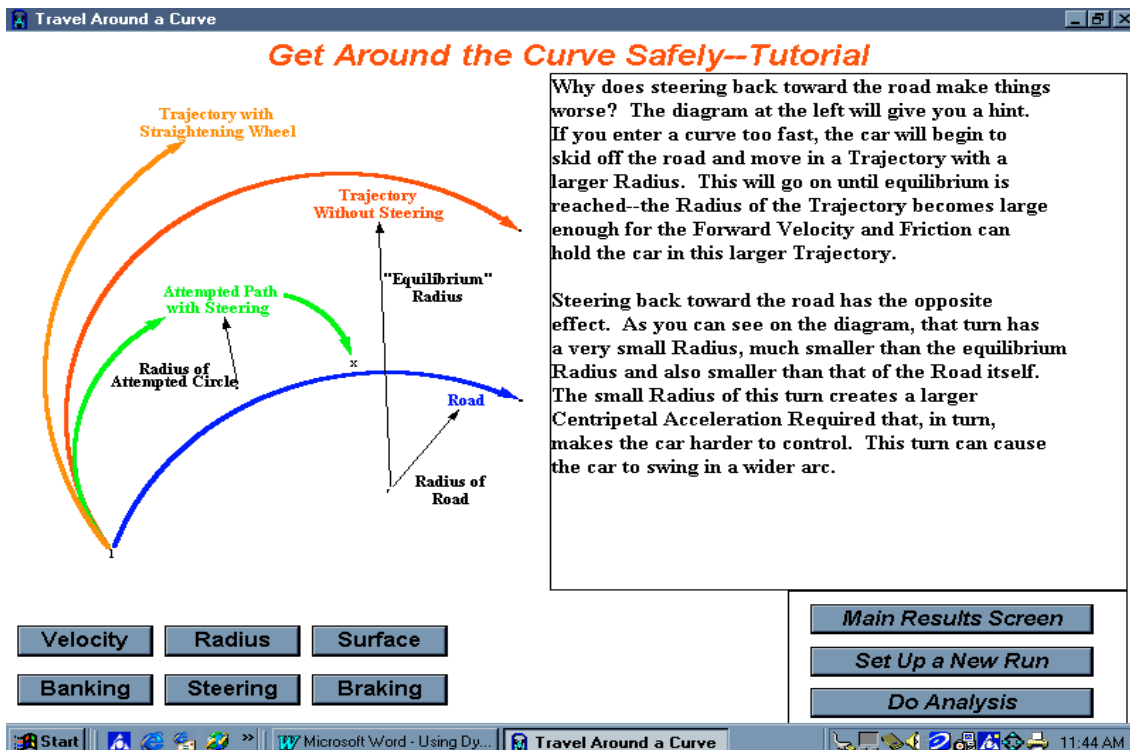


Figure 6: Tutorial Explaining the Effect of Steering in Worsening a Skid

Other tutorials help students understand how the simulation results relate to the mathematical formulae used to explain circular motion and each of the key parameters affect the likelihood that a car will skid off the road on a curve. There is also a tutorial on braking that helps to explain why jamming on the brakes and locking the wheels will result in a complete loss of control and travel in a straight line away from the road.

### **Collisions: The Dynamics of Crumpling and Restraint Systems**

Collisions are another topic dealt with by the Transportation unit in the Active Physics curriculum. Students are encouraged to think about how restraint systems protect people and do experiments with carts to understand the effects of rear-end collisions such as whiplash injuries. The collision simulator lets them scale up their analyses to cars and trucks without the obvious risks inherent in real world experiments.

Traditional physics texts do not generally treat collisions as a dynamic phenomenon. They concentrate on using formulae that apply conservation of momentum to calculate post-collision speeds and directions of objects that collide. There are two areas however, where dynamics are important. One is the effect of crumpling by vehicles and stationary barriers in spreading out the collision over time and thereby reducing the rate of deceleration of the car and acceleration of occupants with respect to the car. The other is the effect of restraint systems in absorbing the forces on occupants as they accelerate with respect to the car and also spread those forces out over the occupant's body.

The simulator deals with both the traditional emphases on post-collision velocity and direction and the dynamic aspects that are especially important for understanding how occupants will fare in a crash. (This is critical for teenagers who may be less experienced drivers, drive older cars without airbags, and forget to put on their seat belts.) Figure 7 shows the one of the setup screens that let students choose the type (and therefore the mass), velocity, and direction of the other vehicle they will be colliding with. They have already chosen their own vehicle and velocity. For simplicity, they're always assumed to be traveling East. As with the first simulator, the buttons at the bottom suggest experiments that isolate the effects of particular factors.

Figure 8 shows the results of a pair of crashes between a vehicle and a stationary barrier. These were set up using a different input screen that lets students specify the speed and type of their own vehicle, the angle of incidence, and the nature of the barrier: concrete, wood, or an energy-absorbing array of water-filled barrels. The simulations both involve sedans traveling at 20 meters per second hitting the wall straight on, but one assumes a concrete barrier while the other uses the energy-absorbing water barrels. The results are dramatically different. The total crumple distance (compression) is three times as great as a result of the flexible water barrels and the time constant of the crash is three times as long as the one into concrete. The Maximum Rate of Deceleration with the energy-absorbing barrier is represented by the shorter more spread-out peak (in blue) compared to the narrow, tall peak for the concrete wall (red line). The decrease in velocity with the energy-absorbing barrier is more gradual as a result.



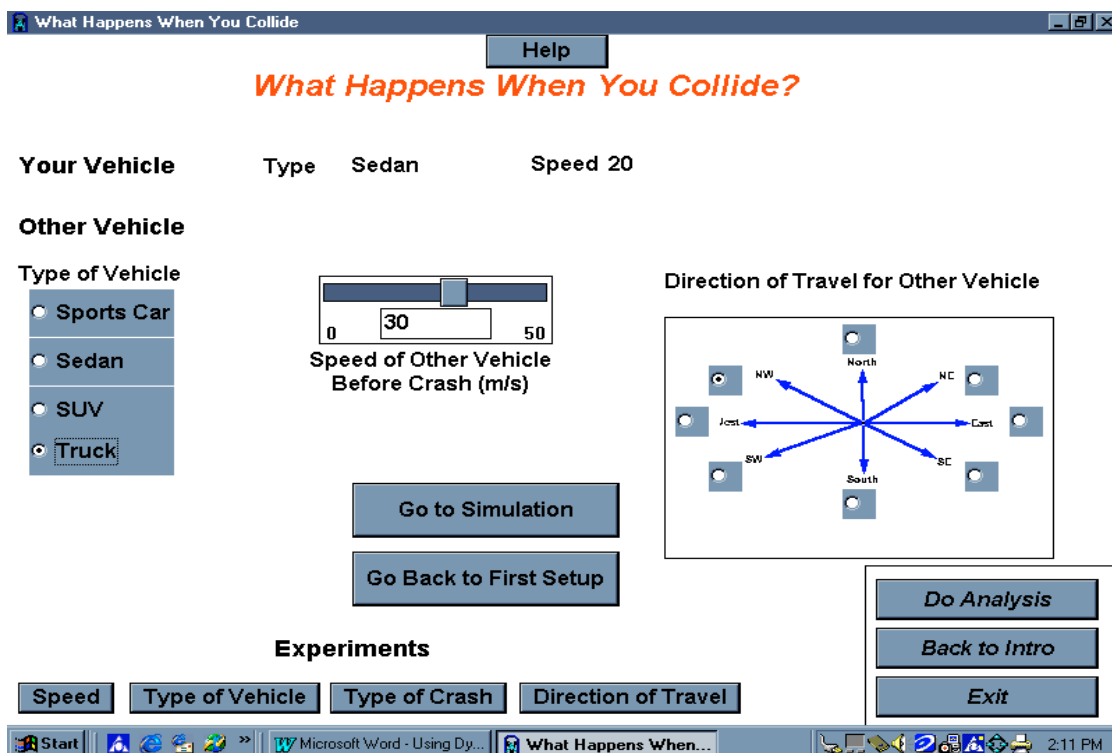


Figure 7: Input Screen for Setting Up Collision Experiments

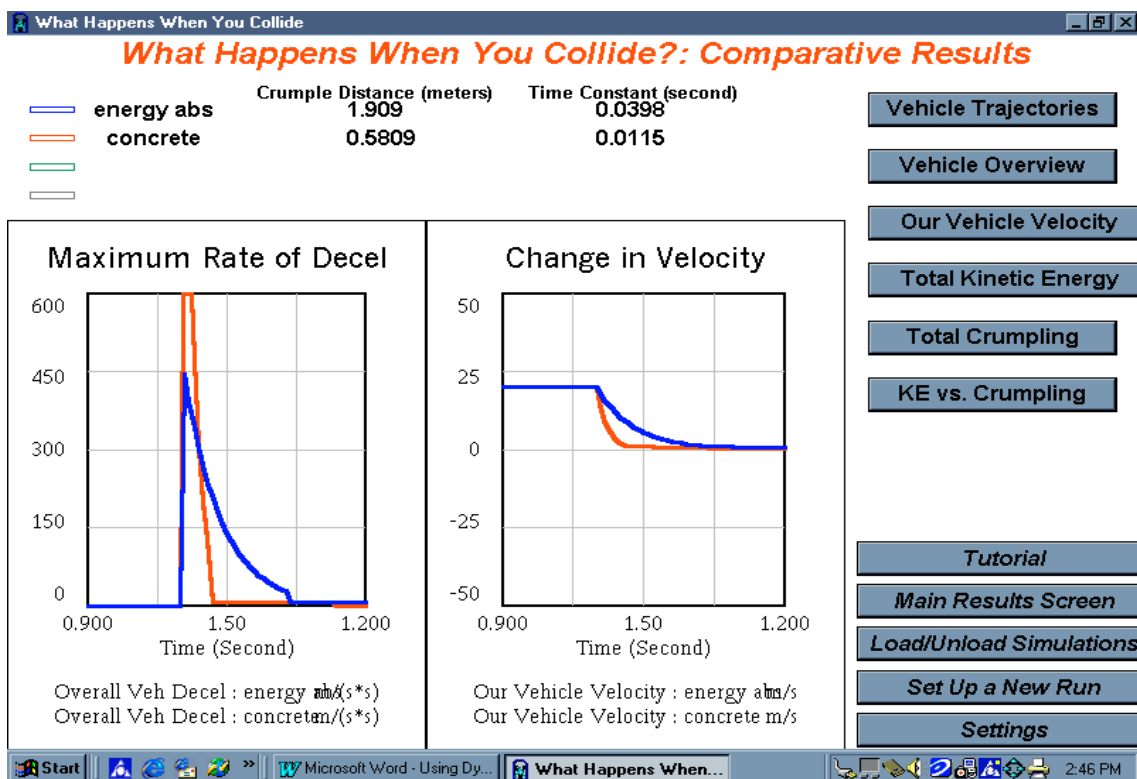


Figure 8: Results of Collisions Against Concrete vs. Energy-Absorbing Barriers

What are the implications of the differences in these two crashes for the occupants, especially if they are not using a restraint system? Figure 9 shows results for the two crashes when occupants are and are not using restraint systems (lap and shoulder belts). The rates at which the two vehicles decelerate are, of course, only affected by the nature of the barrier. The deceleration of the occupant (Deceleration Due to Restraint) is affected by both the barrier and restraint system. The much lower, spread out peak in that graph (blue line) represents the combined effect of the energy-absorbing barrier and restraint system. The taller, narrower peak in that graph (red line) is the deceleration due to the restraint system in the crash into the concrete barrier. The forces exerted per square inch on the occupants are also drastically different with and without the restraint system.

As you can see in the table in the lower right-hand corner, there is a more than twelve-fold difference in the force per square inch. This is partially due to the more gradual deceleration with the restraint system and also the result of the lap-and-shoulder belts spreading the force over more square inches (than if the unbelted occupant hit a small area of forehead on the windshield or dashboard). These kinds of insights are not available to students with the traditional approach that focuses on the transfer of momentum and does not deal with the dynamics of the occupants' motion during a crash.

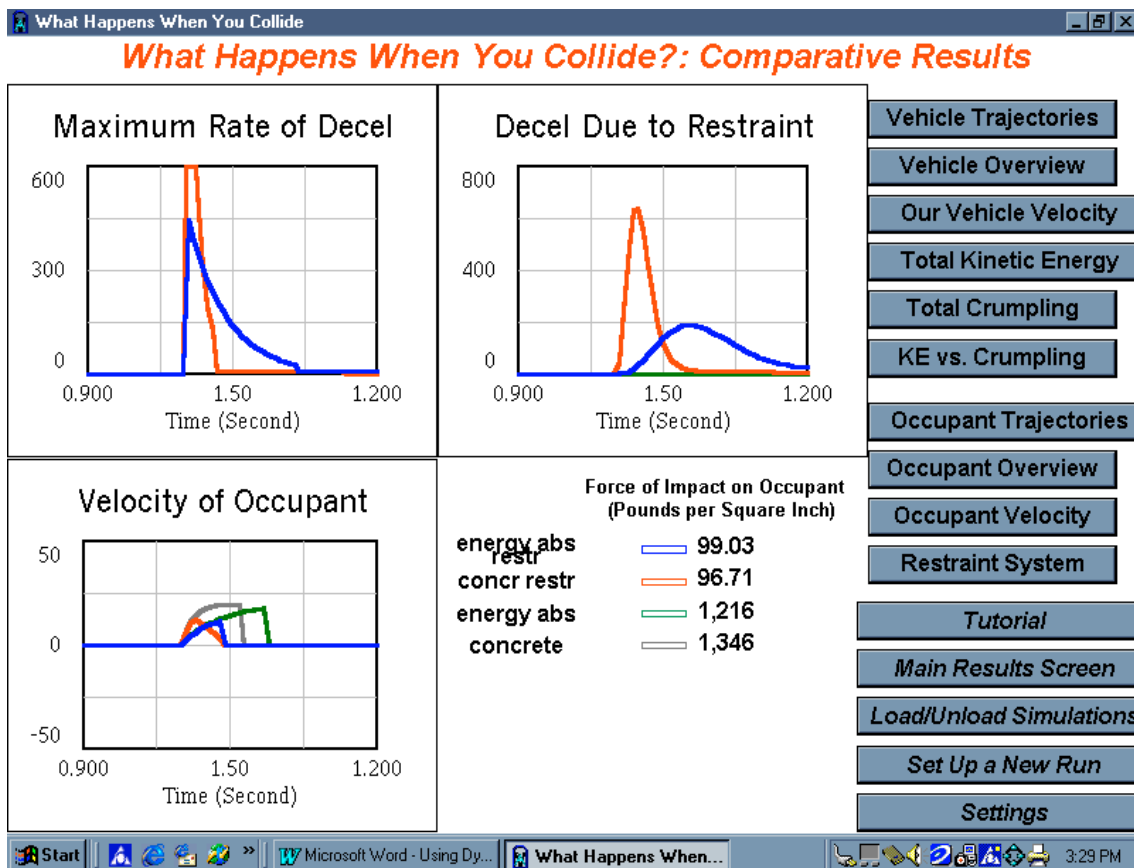


Figure 9: Effects on Occupants of Crashes with and Without Restraint Systems Into Different Types of Barriers

The simulator also enables students to integrate this dynamic view with the traditional emphasis of post-collision velocity and direction. Figure 10 below shows the results of a crash of a sedan traveling East at 20 meters per second with a truck traveling toward the Northwest at 30 meters per second. It shows the sedan being thrown backwards and to its left while the occupant appears to move in the opposite direction (front and to the right) with respect to the inside of the car. The picture in the upper right-hand corner also provides a sense of the occupant's movement. The graphs at the bottom show how the occupant accelerates briefly, reaches a peak velocity, and is restrained by the lap-and-shoulder belts. The picture moves in conjunction with simulation results and gives students a more realistic sense of the direction in which an occupant might be thrown.

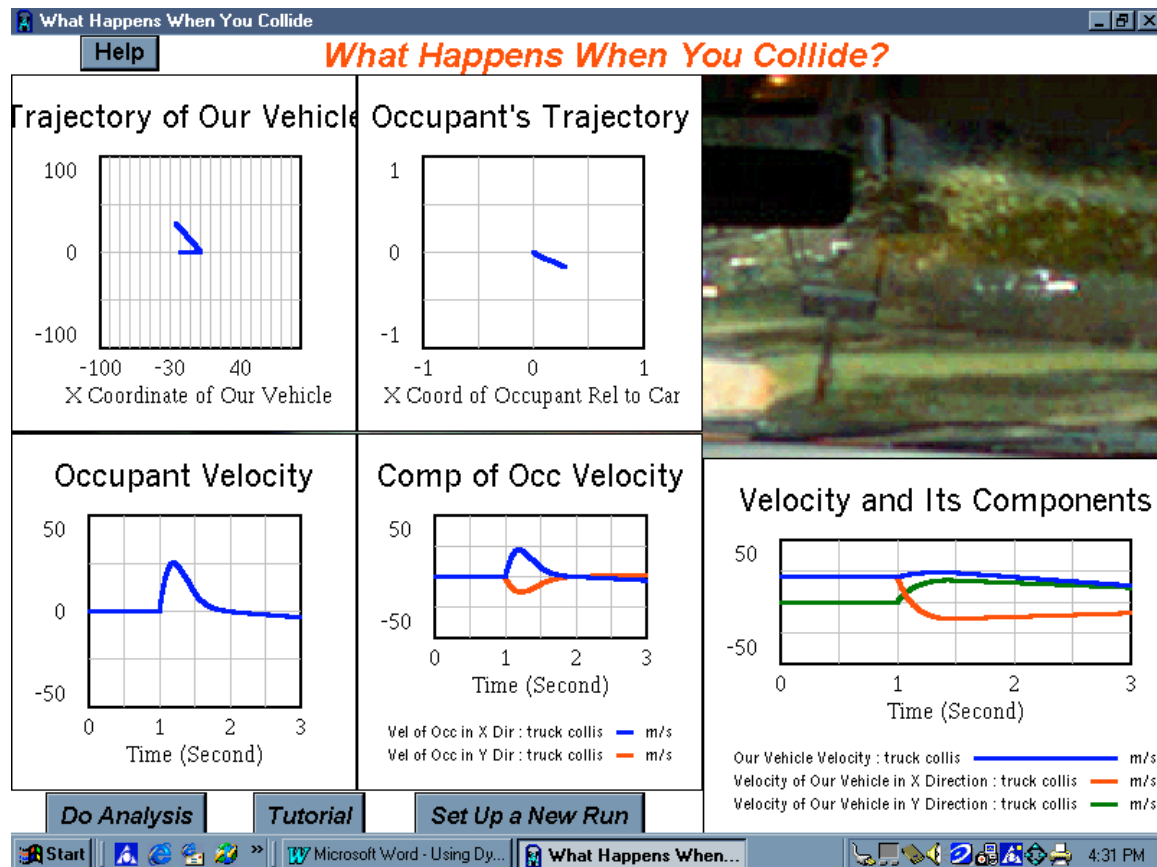


Figure 10: Results of Crash Between Sedan and Truck

In addition to a wide range of experiments and tutorials, the simulator also has some built-in challenges that can serve as assessment tools and help to determine how well students have understood the material. One is a design problem involving a barrier in an area where there have been many accidents. The other is an accident investigation problem.

## Heat Flow and Energy Conservation in the Home

Home heating is the classic example used to illustrate the operation of feedback systems. A thermostat controls a furnace, turning it on frequently enough to maintain a constant temperature indoors regardless of the temperature outside. However, traditional physics curricula usually just deal with heat flow between objects. The Active Physics Home unit focuses on heat flow into and out of dwellings and has students do experiments with heat lamps and cardboard models. It also gets students to think about the economic implications of the physics and how investments in insulation and other energy conservation measures save money. The Heat Flow simulator enables students to scale up their investigations from cardboard models to a house and try many more variations than they could with physical artifacts.

Students are first introduced to four different types of heat flow (conduction, infiltration, solar, and from heating and cooling systems) as shown in Figure 11. The feedback loops that drive heat flow over time are shown in the diagram. One is the loop mentioned earlier in which the difference between a target indoor temperature and the current temperature causes heat to be added or taken away from the house and brings the indoor temperature closer to its target. Another is the one in which the difference between outdoor and indoor temperature drives the flow of heat into (in summer) or out of (in winter) the house via conduction. A similar loop exists for infiltration, the flow of heat embodied in air that moves through tiny openings in the outside walls. Thus feedback is an important mechanism for establishing temperature equilibrium even before any heat is added or taken away. By using the simulator, students come to understand that these feedback loops work together to determine heat flow and energy use.

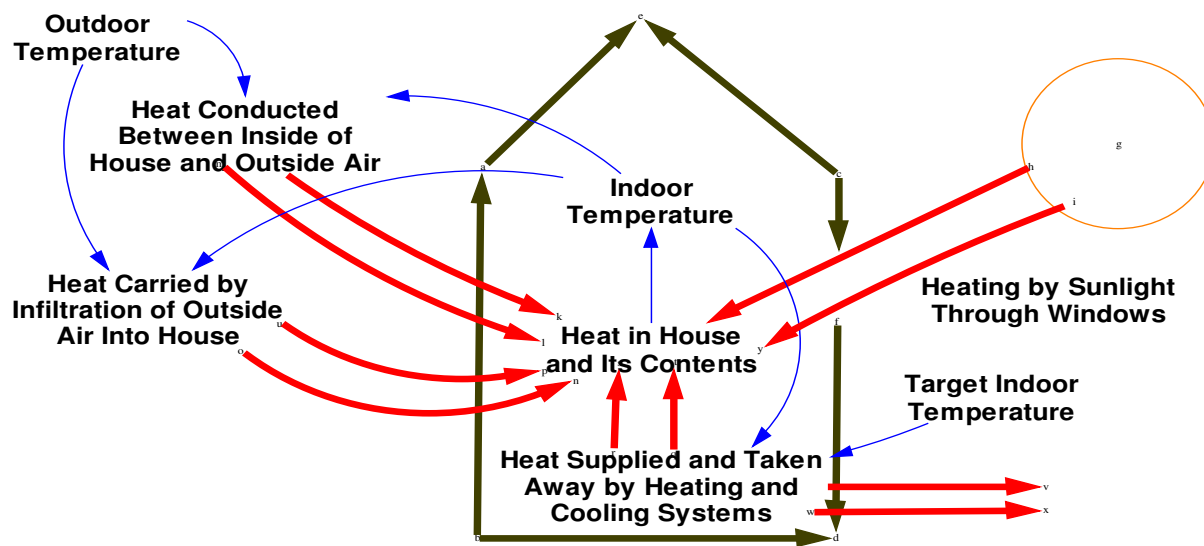


Figure 11: Determinants of Heat Flow Into and Out of a House

Before experimenting with heating and cooling systems, students are first encouraged to repeat experiments they did with cardboard models, but at the scale of a house. (This is an example of how a simulator can help to structure students' explorations.) These simulations study what happens to a house in the Middle-Atlantic states in the US during a summer day as the outdoor

air heats up. In one (exper1-red line), there is effectively no insulation while in the other (exper2-blue line), 3 inches are provided in the wall and 6 inches in the ceiling. Figure 12 shows the resulting heat flow and indoor temperature with and without insulation. The large peak in heat flow with no insulation (exper1) in the left-hand graph shows how the difference between indoor and outdoor temperatures during the day drives conduction. The much smaller peak (exper2) shows how insulation resists heat flow. As a result, the temperature increase over the course of the day, shown in the right-hand graph, is 2 degrees lower.

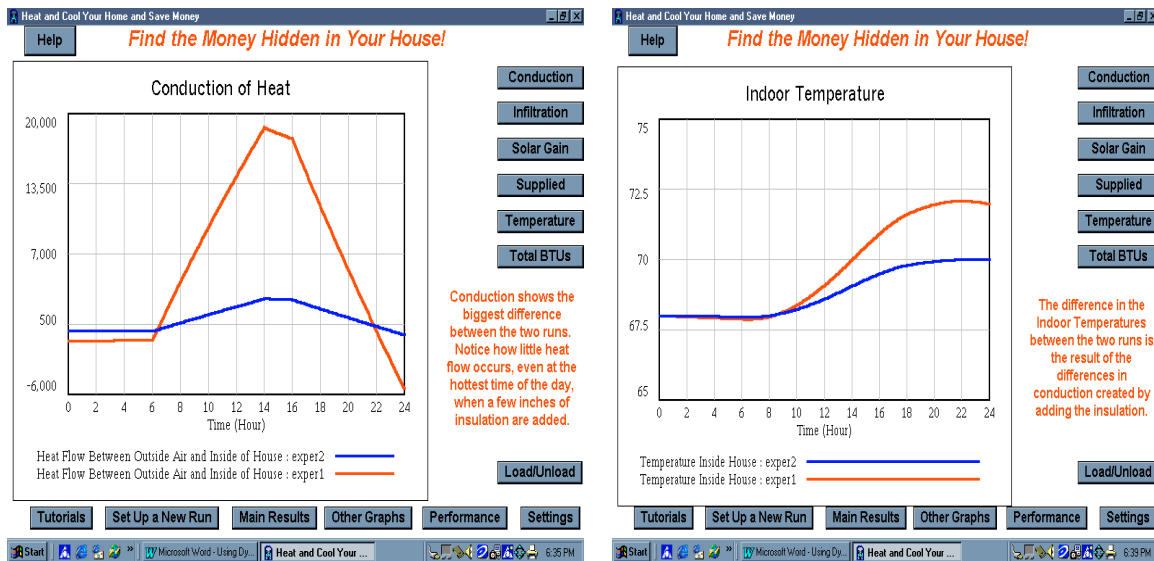


Figure 12: Heat Conduction and Temperature Change on a Summer's Day--  
With and Without Insulation

Students can continue experimenting with passive heating and cooling, trying, for example, the same experiment on the same house in winter or in a differently constructed house. They can also add heating and cooling and exploring how different options affect heat flow and the energy and cost required to keep a house at a comfortable temperature. Students can have the simulator automatically calculate the required size of the heating or cooling plant for the house they have selected or can go through a tutorial that helps them do this calculation. Figure 13 shows an input screen that reveals some of the choices available to students. There is another screen that deals with insulation, double windows, overhangs and shades, more efficient furnaces and air conditioners, and solar heat.

For example, a student might want to experiment with different sized heating plants and then look at the effect of insulation in lowering heating requirements. Figure 14 shows the results of three experiments that a student might set up, using a 1500 square foot house in the Northern part of the US in January. The house initially has drafty construction and no effective insulation. The student starts with a heating plant of 40,000 BTU's per hour and then doubles that to 80,000 BTU's per hour. A third simulation tries the 40,000 BTU heating plant again, but with 3 inches of insulation in the walls and 6 inches in the ceiling

Figure 13: Input Screen for Heating and Cooling Experiments

The results in Figures 14 reveal that the 40,000 BTU heating plant (green line) is not sufficient for what the climate and house require. The heat must stay on all the time (as shown by the line straight across in the upper left-hand graph) and the temperature indoors (in the upper right-hand graph) still drifts downward over the course of the day to a level that is uncomfortable, but somewhat above what it would be with no heat at all. The heating plant still uses enough fuel to produce 880,000 BTU's over the course of a day (lower left-hand graph) even with this undersized plant and less-than-adequate comfort.

The fourth graph helps to explain why a constant temperature cannot be maintained. It shows that at most times of the day, the house is losing more than 40,000 BTUs per hour due to conduction alone. An additional 10,000 to 25,000 BTUs per hour is also lost due to infiltration. A 40,000 BTU heating plant has no way of keeping up with the flow of heat out of the house. (Negative values on the graphs signify flow of heat out of the house. The flow becomes less negative during the middle of the day when outside temperature rises and the difference between indoor and outdoor temperature is less).

The 80,000 BTU heating plant (red line) is able to overcome this flow and maintain a comfortable temperature, but uses a lot more fuel to produce about 1.5 million BTU's.

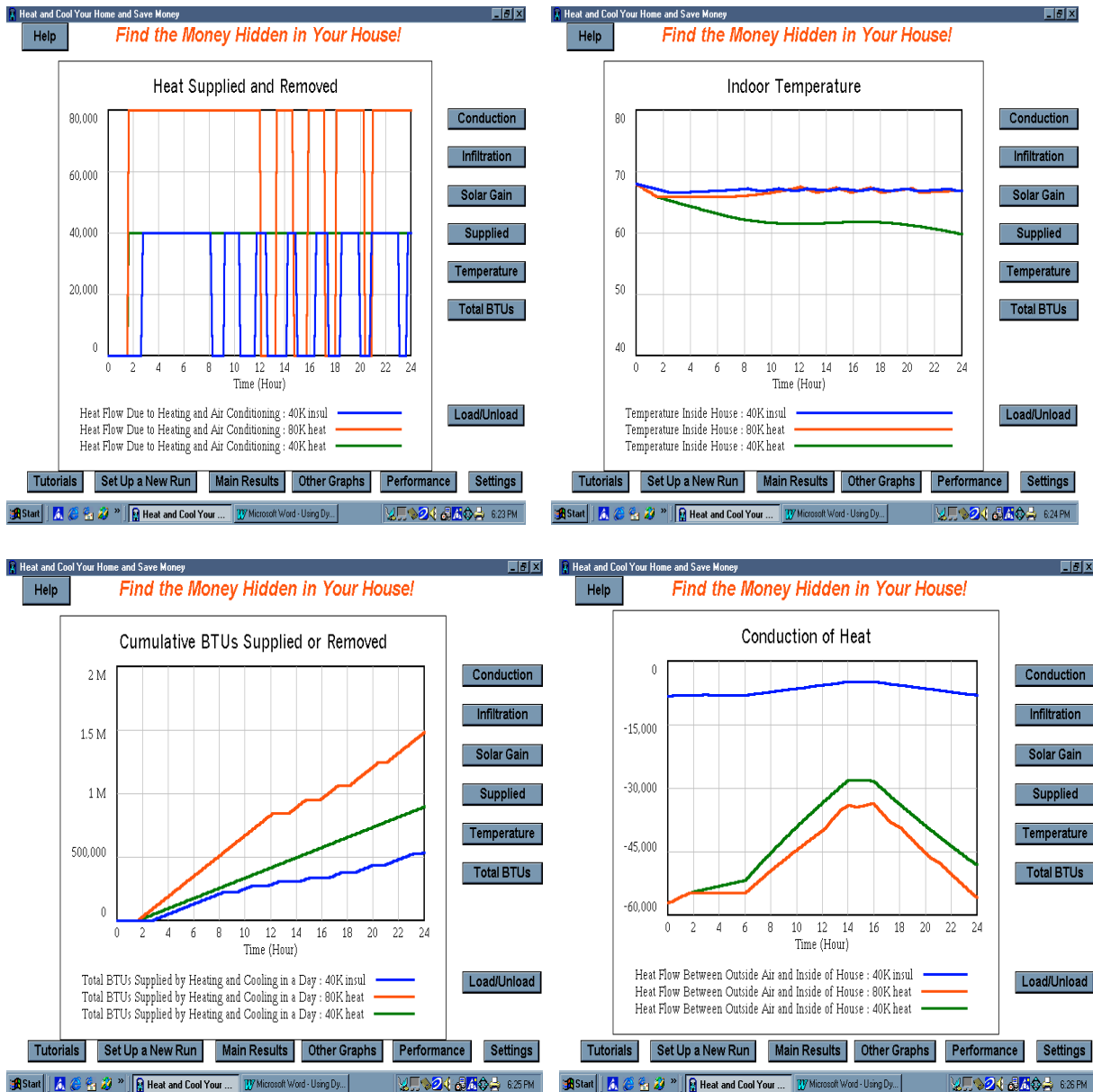


Figure 14: Results of Simulations with Different Heating Systems and Insulation

The student will find that the third simulation (blue line) provides the best results. By adding insulation, the 40,000 BTU per hour heating plant that was inadequate before now can maintain a constant temperature with much lower fuel consumption. The reason why is clear in the lower right-hand graph that shows conduction of heat is considerably less because of the insulation. (The blue line shows a less negative value, signifying less conduction of heat from the house to the outdoors.) As a result, the heating plant does not have to work nearly as hard to maintain a constant temperature.

Students are also able to translate these results into economic terms. Figure 15 shows a table generated by the simulator that compares the annual cost incurred in the three simulations that have just been described. The last simulation, the one with the 40,000 BTU heating plant and

the insulation (40K insul) has the lowest cost. (The capital cost shown reflects only the cost of the insulation. The cost of the heating plant is assumed to be a "given".) A tutorial helps students do a cost-benefit analysis using these data and tells them how to calculate a return on investment from various energy conservation measures.

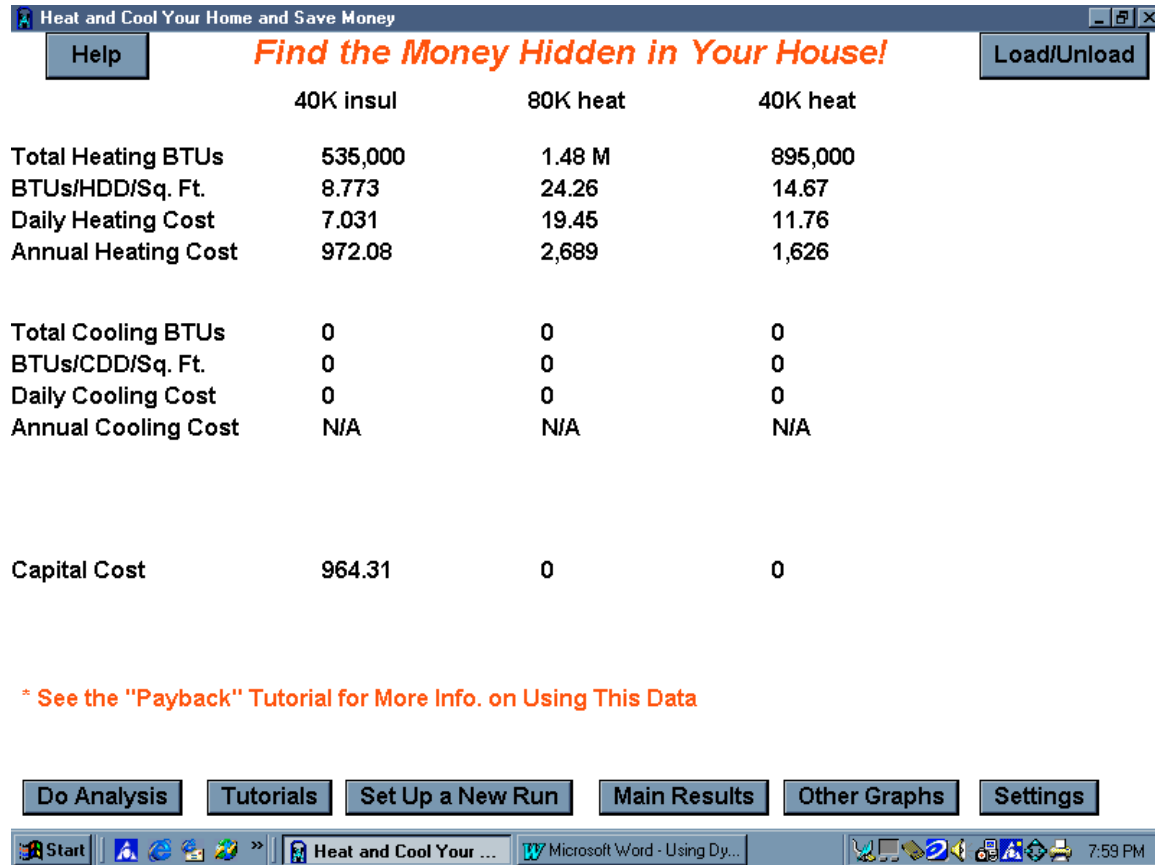


Figure 15: Economic Implications of the Three Simulations

### Pole-Vaulting: Using Sports to Understand Energy Storage and Conversion

It's quickly apparent to students that pole-vaulting is a dynamic process, but the fact that it is really a series of energy transfers, spilling energy from one "bucket" to another is less obvious. Figure 16 shows the causal relationships involved as the runner's kinetic energy is first stored in the bent pole and then, as the runner leaves the ground and rises above the floor, is converted to potential energy. The height of the vault is affected by the runner's speed, the material in the pole that affects the amount of energy that can be stored and the percentage of energy lost, and additional energy the runner is able to inject at several points. These include using upper body strength to bend the pole further, thrusting with legs at takeoff, and pushing down on the pole at the top of the arc.



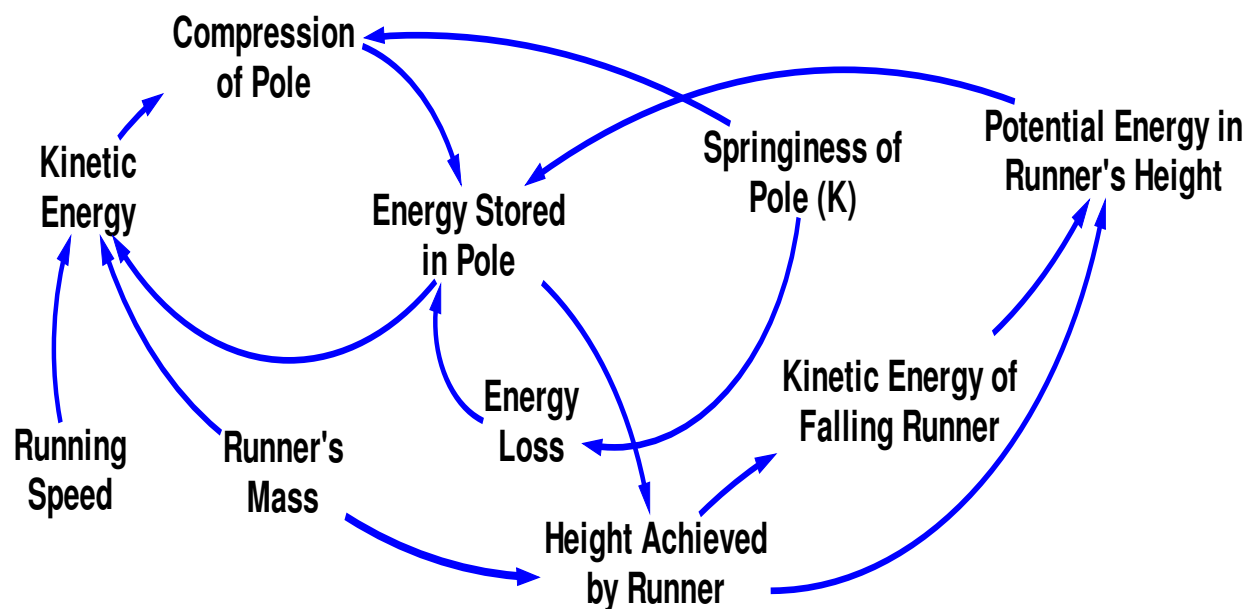


Figure 16: Causal Relationships Involved in Pole-Vault

A traditional physics text might simply ask students to calculate the vault height of a runner with a particular velocity, making simplifying assumptions about energy conservation. The Active Physics Sports unit gets students to understand the individual energy transfers by doing experiments such as rolling balls down a ramp and hitting the end of a ruler clamped to the lab bench (kinetic to stored in pole). Another experiment uses a bent ruler to launch coins into the air (stored in pole to potential). The simulator then gives them the opportunity to "put it all together" and investigate the energy transfers in series and to manipulate various parameters to determine how they affect the dynamics of the vault and the maximum height achieved. Students start with variations in runner velocity and then get to experiment with other variables such as runner mass, material in the pole (bamboo vs. fiberglass), and whether the runner injects additional energy in the manner described earlier.

Figure 17 shows the results a student would see in the first simulation where a runner is assumed to approach the vault at a maximum velocity of 6 meters per second. The animation helps them associate the energy transfers with the different stages of the pole vault. The graphs in the lower left-hand corner show the measurable quantities such as the runner's velocity (blue), amount of compression in the pole (reduction in length from tip-to-tip) (red), and height in meters that the runner achieves (green). The right-hand graph shows the corresponding levels of energy in each form as the jump proceeds. The top line shows the total energy that should ideally remain constant, but drops because of energy lost due to heating and vibration as the pole bends and straightens. Total energy jumps at the end of the simulation as the center-of-mass, which starts at a standing height, falls to the floor as the runner lands lying down. The student is guided through another simulation with a running velocity of 8 meters per second and sees how the two compare in terms of energy levels at the different stages and the resulting physical measurements.

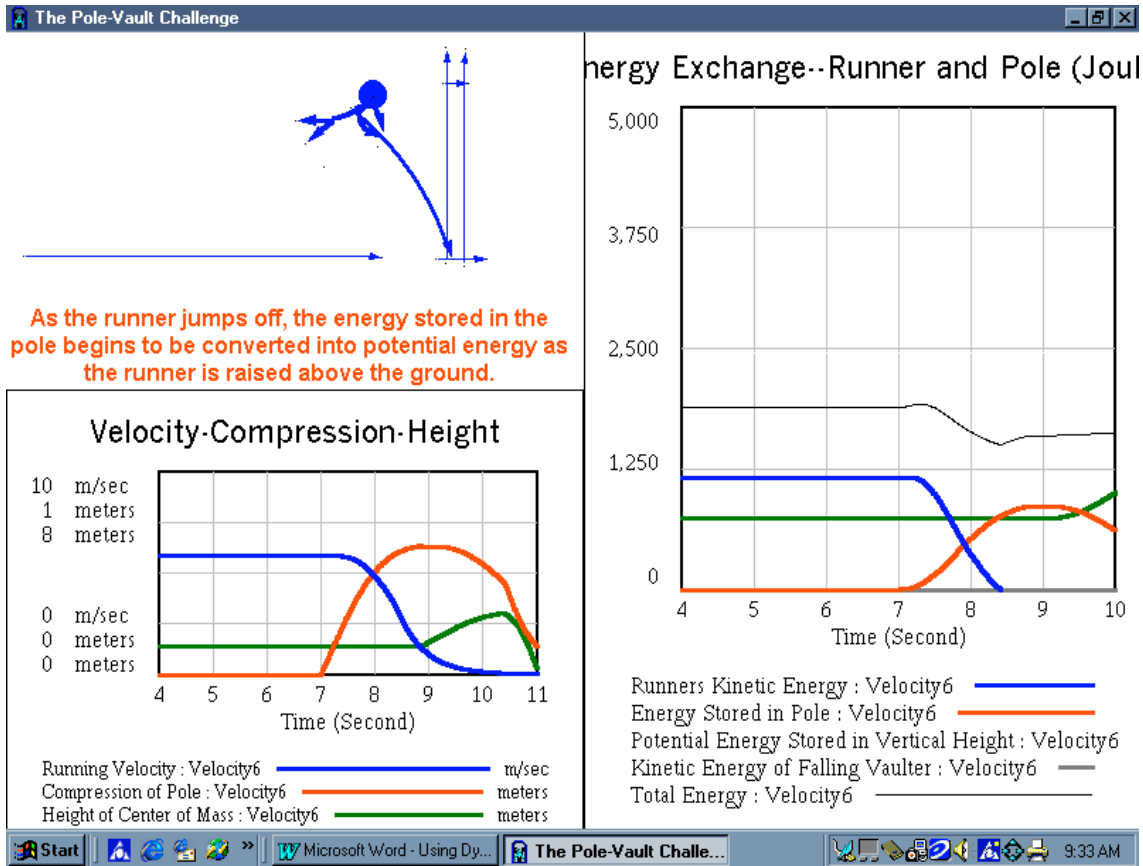


Figure 17: Results of Pole Vault with 6 Meter per Second Running Velocity

After a series of guided explorations, students get to experiment with their own combinations of parameters to develop better intuition about how the various factors interact. Figure 18 shows the selection of variables available for these explorations.

Figure 19 shows comparative results for a series of simulations that a student might do. These are for simulations with running velocities of 6 and 8 meters per second (and no additional energy input besides the kinetic energy of running and a third one with an 8 meter per second running speed and all of the additional energy inputs a skilled pole-vaulter might provide. The graphs compare height attained by the runner's center-of-mass and potential energy realized for these three simulations. Students are able to see the considerable increase in height as a result of going from a running speed of 6 meters per second (green) to 8 (red) and the further increase made possible by a skilled vaulter putting additional energy into the jump (blue). This brings the analysis closer to the real-world pole vault than would be possible by using formulae alone. The formulae would suggest a maximum height of about 3.25 meters for someone running at 8 meters per second rather than the almost 5 meter height which is closer to actual pole vault records.

In addition to many different combinations of variables, the simulator also provides students with the option to try pole-vaulting on the moon. This gives them a sense of how the moon's reduced gravitational force would boost vault heights.

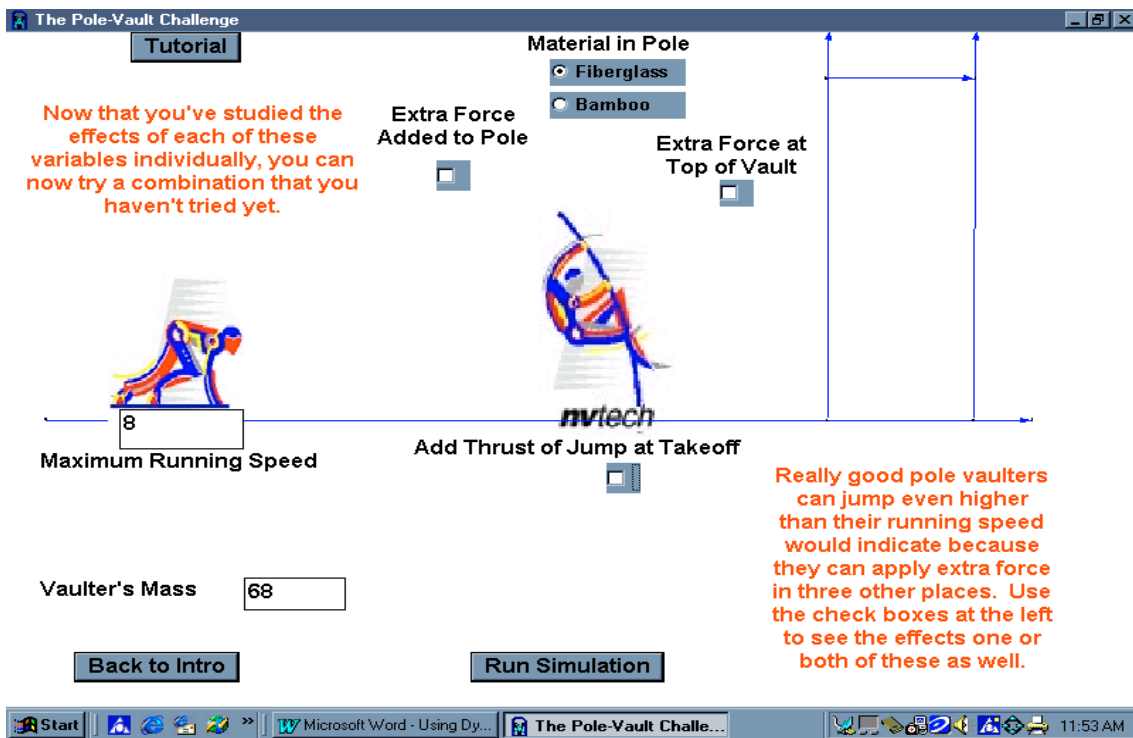


Figure 18: Input Screen for Setting Up Pole Vault Experiments

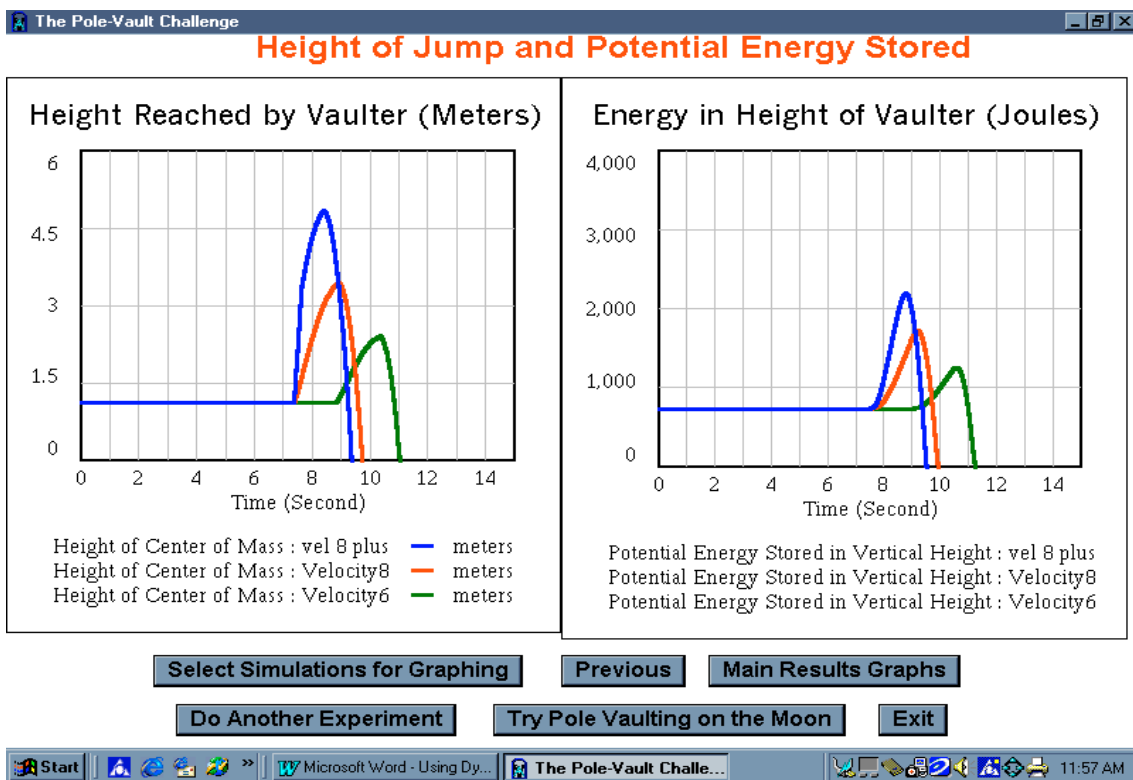


Figure 19: Results of Three Pole-Vaulting Experiments

## **Scaffolding/Scripting and Other Pedagogical Issues**

The simulators described on the preceding pages are very much works in progress and are continuing to evolve in ways that hopefully make them better teaching tools. They have had limited field testing with teachers and students. As indicated earlier in this article, guiding students' explorations is an important role that simulators and curricula based on them can play. A sense developed early on in their development that these simulators presented too many options for students to investigate and that there was the potential for wasting effort and "spinning wheels" as students tried too many different changes at once. This was especially apparent when using the simulators within a standard high school class period of 40 minutes where students must learn very efficiently. An initial response to this problem was the creation of the suggested experiments such as the one for the Travel Around a Curve simulator shown in Figure 3. These suggestions are designed to get students to focus on one variable at a time rather than making too many changes at once. In a class of 24 students organized in groups of 3 around 8 computers, a possible approach would be to have one or two teams focus on each set of experiments and then pool their knowledge at the end of the class period.

Even with this approach, the predominant reaction by teachers and others who looked at the simulators was that they threw too many variables at the student at once. This difficulty seemed to call for an approach that has come to be known as scaffolding or scripting. Scaffolding is gradually building a structure of concepts and understanding, one idea at a time. Horwitz discusses the pros and cons of scripting, indicating that open-ended exploration can be a powerful way of letting students construct their own knowledge, but can also be inefficient and frustrating to students. Some sort of structure is required to achieve desired outcomes during the available time. Scripting provides a means to control the interaction and identify when help is needed to keep students from getting stuck. However, scripting cannot be too restrictive or the value of open-ended exploration will be lost altogether. Flexible scripting or scaffolding can respond to student needs without cutting off exploration. Scripting can be used with built-in assessment to help students explore and learn at an appropriate pace.

Limited scaffolding has been built into these simulators and more will be added in the future. One example is in the Heat Flow simulator where students are first taken through two experiments involving a house going through passive heating on a summer's day. These experiments are analogous to experiments that students do on the lab bench with cardboard house models and heat lamps as part of the Active Physics Home unit. The results of these experiments are shown in Figure 12. These experiments establish a link between the curriculum and the simulator and introduce students to both the mechanics of using the simulator and the way of thinking that it supports. The pole vault simulator has much more extensive scaffolding built in. Students are taken through a series of experiments, adding one variable at a time before given access to the full range of choices shown in Figure 18. Even here, more can be done to introduce concepts gradually and present information in smaller bites.

## **Next Steps**

Near-term development of the simulators is focused on several areas. One is to improve the graphic presentation in order to lower the information density on each screen and support

scaffolding. The simulators will also benefit from advances in interface technology, adding animation to demonstrate concepts and voice-overs to narrate screens rather than having students read large amounts of text. There will also be more emphasis on making the feedback structure of the simulators more explicit and teaching about physical phenomena in terms of feedback, delays, and other System Dynamics concepts.

There are already tutorials built into the simulators that present and use the relevant mathematical formulae. Further work will extend these into "what do you think will happen" exercises to go along with the simulations. One of the teachers using the simulators, Jim Jones of Northfield, Vermont, has also used simulation results with his students as "data", asking them to derive the mathematical relationships that would have produced these results. More will be done with this idea as well.

Finally, there will be more work on building assessment tools into the simulators. Horwitz suggests that learning with computer-based manipulatives may not be easily measurable with pencil-and-paper tests. To the extent possible, assessments will be built into use of the simulators and be supplemented with "offline" exercises including pencil-and-paper instruments. The pilot simulators already contain challenge assignments and design problems that use the concepts learned to deal with a real-world problem such as highway design or accident investigation. These kinds of design problems are what Wiggins and McTighe suggest are the performance tasks necessary for assessing enduring understanding. Assessment will be made more comprehensive with exercises at different points to assess what students have learned and give them additional help with troublesome concepts before they move on.

More field-testing with teacher focus groups and in classrooms are likely to identify additional improvements that will make these simulators more effective. Field-testing will be done with different variants of the simulators in order to answer such questions as "How much scripting and scaffolding is the right amount?" Planned field-testing will also use such tools as pre- and post-testing to identify the impact of the using the simulators along with Active Physics units on learning compared to using the Active Physics units alone. These field tests should provide valuable data on the benefits of simulation in general for learning as well as specific evidence of the impact of these simulators.

### References

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