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The Energetics of a Bouncing Ball

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Typical introductory textbooks begin the study of kinematics by introducing the concepts of work, kinetic energy, and gravitational potential energy. They often include a discussion of the work-energy theorem and then move to conservation of energy. One popular example used to illustrate this concept is the object dropped or thrown perpendicular to the ground with some initial speed from some initial height. The example usually asks for the speed of the object when it is some other distance above the ground.

From the teacher's perspective, this is a particularly nice question because it gives a very rapid and, typically, easier solution to a problem that has already been approached using equations of uniformly accelerated motion. It is equally productive and enjoyable from the students' perspective—until they are asked to consider the situation at just that instant when the object hits the ground. At this point at least one student will suggest that the object has stopped and isn't moving; that is, its velocity is zero. You can be sure that other students are thinking the same thing: ask for a show of hands for how many students agree with that suggestion. Of course other students will understand that you are speaking about that instant when the object has just reached its maximum speed and is beginning its collision with the ground. Interaction between these two groups usually brings them where you want them: to a rudimentary exploration of energy conservation.

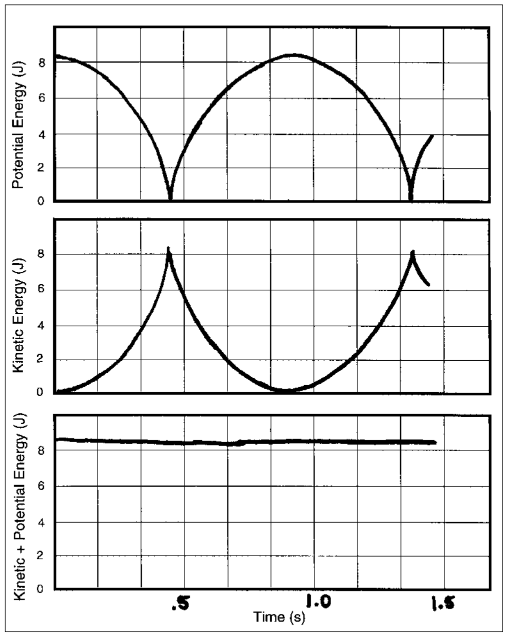

Fig 1. Typical graphs of student predictions for potential, kinetic, and potential + kinetic energy vs time. Mass of ball is 0.85 kg. An initial height of 1.0 m was assumed.

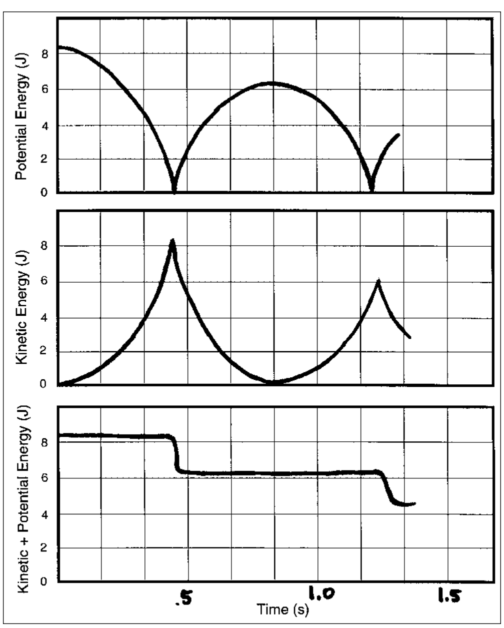

Fig. 2. Revised graphs include the observation that the ball does not bounce to the same height from which it began. Mass of the ball is 0.85 kg. An initial height of 1.0 m and a return bounce of 75% of the original height was assumed.

The traditional next step is to progress to other examples of conservation of energy. We have found, however, that it is interesting and useful to pause at this point and look more closely at the specific example of the energetics of a dropped ball as it falls and bounces.

Pre-Lab Exercise

We begin the activity by asking our students to create careful sketches of graphs of potential energy, kinetic energy, and the sum of the kinetic and potential energies, each as a function of time. The object in question is a large rubber playground ball that will be dropped from a point near the ceiling of the room and will bounce off a tabletop or the floor. Students use an electronic balance to measure the mass of the ball and a tape measure to determine the approximate height of release; then they can set an appropriate energy scale for their graph. (Students have just been shown that the mass of the object need not be known to calculate the theoretical speeds attained at different heights, so they often must be reminded that the mass *is* necessary to calculate actual energies.)

Construction of these graphs is usually left as a homework exercise. A typical predicted graph is shown in Fig. 1. The division of the time axis is intentionally left to the student's discretion. This is an acceptable attempt: it shows total energy to be conserved and a parabolic shape to both the kinetic and potential energy curves. We press students on these graphs before allowing them to perform the experiment by reminding them that a graph like Fig. 1 implies that the ball returns to its initial height after it has bounced. Students will typically revise their predictions at this point to look more like those shown in Fig. 2. They must, of necessity, make an estimation of how high the ball will bounce to produce this graph.

Experimental Setup

The experimental setup is shown in Fig. 3. Now we will use real-time data acquisition and graphing applications.[1] A motion detector is suspended above the ground or taped to the ceiling. This allows multiple bounces to be recorded and eliminates the obvious potential for damaging the detector by bouncing a ball from it. The detector software is configured so that it reads zero when it detects the top of the stationary ball sitting on the ground; positions closer to the detector are read as positive distances. Now the ball is dropped from a position just below the detector, but far enough away so that the detector properly records the position. Sample position-vs-time and velocity-vs-time graphs for such a drop are displayed in Fig. 4. It is difficult to coordinate the dropping of the ball with the start of the detector sampling. Ideally, the ball is held steady and not released until after it has been observed that data is being collected by the detector, so the dropping of the ball does not coincide with time $t = 0$ s. This must be taken into account when comparing predicted and actual graphs. Logger *Pro*™ software also allows the user to create new columns of values using the data already collected. This feature is used to produce graphs of potential energy, kinetic energy, and kinetic plus potential energy versus time from both the position- and velocity-vs-time graphs. Figure 5 displays graphs of these quantities created from the data shown in Fig. 4.

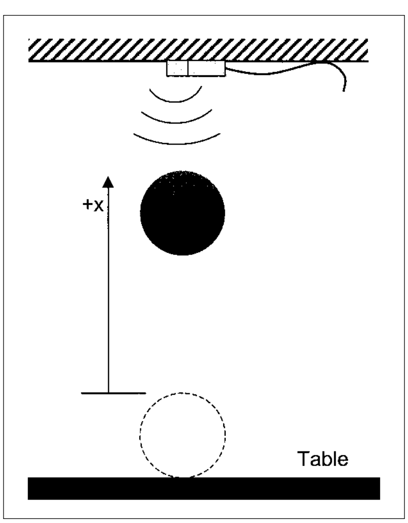

Fig. 3. Experimental setup.

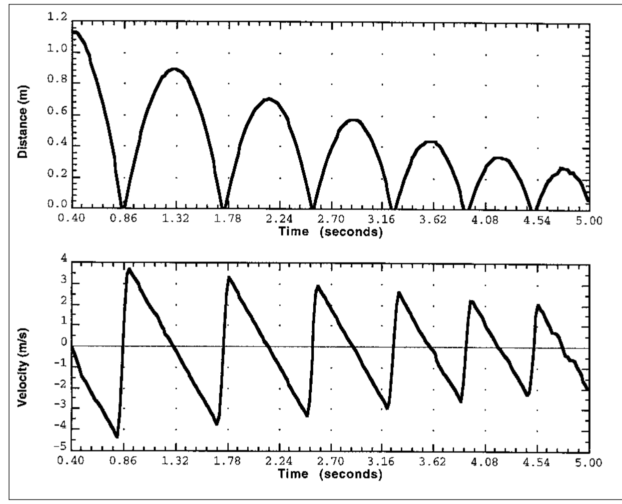

Fig. 4. Distance-vs-time and velocity-vs-time graphs created by MacMotion application. The sampling rate was 50 times per second and the data was averaged over 5 points.

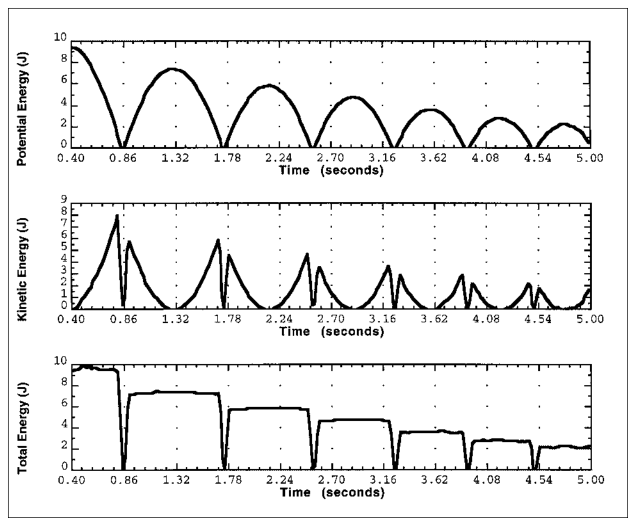

Fig. 5. Graphs of potential energy, kinetic energy, and potential plus kinetic energy vs time created by MacMotion application. Mass of ball is 0.85 kg; a value of 9.8 N/kg was assumed for acceleration due to gravity.

Interpreting the Graphs

It is immediately obvious that something more is happening here than the students predicted. In fact, the sum of the kinetic and potential energy goes to zero. Why does this happen? The students discover that there is indeed a point in time when the ball is simultaneously on the ground—having no gravitational potential energy—*and* changing direction with an instantaneous velocity of zero—having no kinetic energy. This is precisely the situation that students considered in the introductory discussion of conservation of energy! (We should note that an occasional student will grapple with this point as part of the prediction process, but will seldom come up with predicted graphs that incorporate this information.)

The students are then confronted with an obvious question. If we are to believe that conservation of energy is valid, then where did the energy go? Some of the energy appears to be lost forever, as evidenced by the monotonic decrease in the ball's height as it bounces. Students are quick to note the sound produced by the ball and are willing to believe that some of the ball's energy is transferred to the vibrations of the atoms in both the

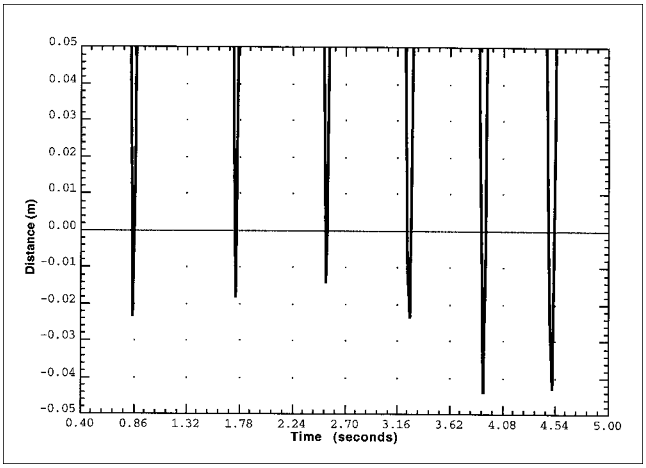

Fig. 6. Distance-vs-time graph created by MacMotion application. Note difference in scale between this figure and Fig. 4.

floor and the ball, i.e., the energy is dissipated as heat. Many are surprised by the insignificant amount of energy lost due to air friction as evidenced by the constancy of the total energy plateau between bounces. On the other hand, a portion of the energy seems to reappear after the bounce, suggesting that it is stored as potential energy during the bouncing process. A significant clue to what is happening can be found by careful inspection of the distance-vs- time graph shown in Fig. 6. The graph clearly dips below zero during the bounces! Either the ball is moving sideways, out of the cone of sight of the detector, or it is compressing as it bounces. The ball bounces many times within view of the detector, so we reject the first possibility as being entirely responsible for this observation and focus on the second. If the ball is "squishing" down, then we can draw a quick parallel to a spring. This serves as a fine introduction to the notion of elastic potential energy.

At first glance it would be convenient to interpret the entire interval of time over which the kinetic-plus-potential-energy curve transitions from one straight-line section to another as the period during which the ball is colliding with the floor. However, the fitting process used to calculate the velocity graph from the position points uses as many as nine position data points. Thus, the influence of a single position data point below zero extends far to either side of that time in the velocity-vs-time graph and hence influences both graphs (kinetic-energy and kinetic- plus-potential-energy vs time.) It is also tempting to interpret the interval of time during which the position-vs-time graph is negative as the collision time. The discreteness of the temporal sampling for the position points can introduce significant errors when the data are interpreted in this way.

Our discussion of this experiment is usually set aside at this point while we explore Hooke's law and use a consideration of work to derive the equation for the elastic potential energy of a spring. This gives us one more place to look for energy in our conservation questions. We can return to the bouncing-ball activity to calculate an approximate spring constant for the rubber ball. One simple method is to use the equation for elastic potential energy and see what spring constant value will account for the missing energy stored during the bounce, given the amount of compression measured in the experiment. This is only an approximate technique: the rate of energy conversion due to friction and other sources during the bounce is unknown. As mentioned earlier, another source of error is the difficulty in measuring the ball's deflection during the bounce. Still, the spring-constant values calculated by students are similar to values calculated by applying known forces and measuring the ball deflection.

Comments

If the class has already explored the concepts of impulse and momentum, it is interesting to use the integrative feature of the software to find the area under the acceleration-vs- time curve during the bounce and to use it to estimate the impulse of the collision between the floor and the ball. The corresponding change in velocity of the ball calculated from this quantity matches the experimentally derived data read from the velocity-vs-time graph. It is also possible to estimate the average force of the collision from this information from an estimate of the collision time obtained from the motion graphs.

It is possible to use this experimental technique to explore several other interesting facets of falling objects. For instance, rotational energy can be introduced by consideration of the Maxwell wheel.[2] For our experiment we intentionally choose a large, relatively massive, playground ball to avoid, as much as is possible, complications that arise from air resistance. A Ping-Pong ball, which is noticeably affected by air resistance during a drop from even a few meters, could easily be substituted to explore these effects.

We have no empirical data on how well students respond to conservation questions "before" and "after" this activity. However, it clearly addresses an obvious difficulty identified by their prediction graphs. Furthermore, it reinforces the complexity of the problem and validates their initial response to the falling-object question, while allowing them to accept the limitations of the model later imposed. Moreover, it pleases students that the teacher has not entirely sidestepped a potentially complex issue.

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1. MacMotion (1989-1994) and Logger *Pro* (1997, for Windows® or Power Macintosh®) available from Vernier Software, Tufts University, and Vernier Software).
2. B. Percori and G. Torzo, "The Maxwell wheels investigated with MBL," *Phys. Teach.* **36**, 362-366 (1998).