Hands-on Physics for Less than a Dollar per Hand

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Because of the continuing problem of inadequate funding for science laboratories and demonstration equipment, teachers must constantly search out low-cost means to foster student participation in physics classes. Following are some truly inexpensive activities and demonstrations that have not, to my knowledge, been published before in the form shown here. (I presented a few at the April 1994 joint meeting of the APS and AAPT.[1]) Many of these hands-on activities illustrate basic concepts that are often overlooked. Some can be done for less than a dollar per hand; a few have zero cost. Thus it will be no disaster if a piece breaks or disappears.

Acceleration and Forces

Acceleration. A common elevator activity is "feet-on"; students stand on bathroom scales in an accelerated elevator. They can also observe the weights of masses hanging from spring scales. A suggested cost-free (but qualitative) alternative is to have the students jump when the elevator is stopping. But it is far more striking if they simply *walk* back and forth. In this way the student always has at least one foot on the floor; when the acceleration is downward the floating sensation is very powerful. The lead-footed feeling during upward acceleration is also impressive, even on a slow elevator (which may stop very quickly).[2]

Free fall: Thrown balls and bodies. Throw a ball straight upward. What is its acceleration at the moment that it stops rising? Some say zero, but gravity is still in force, so that can't be correct. Arons[3] discusses dropping a ball in an elevator that is rising at constant speed. Until the ball hits the floor, an observer outside the elevator sees the ball rise, stop, and then fall, but to a person inside the elevator it is always falling, with constantly increasing speed (constant acceleration). It is easy to prove that acceleration must be the same in both frames of reference, if neither *frame* is accelerating. Thus the ball has acceleration even when its velocity is zero.

This is also clear from a graph of the ball's velocity v versus time; the slope is the same at all points, including the point where $v = 0$. This exercise has a practical side: Because your acceleration can be large even when your velocity is very small, you should keep your seat belts fastened until the airplane comes to a complete stop. (Perhaps it would be a good idea to have seat belts on buses, as they do in Japan.)

Free-fall activity 1: Magnet and keeper. A small magnet is attached to a piece of plastic, which is bent so that an iron "keeper" can rest on a shelf below the magnet [Fig. 1(a)]. Such magnets are available in large quantities for fifty cents or less; the keeper can be a small piece cut from the rod in a hanging file folder. (The large demonstration size of this activity is well known.) When the assembly is vertical, the magnet is not strong enough to lift the weight of the keeper. But when the whole assembly is dropped, the keeper and magnet instantly come together, making a distinct sound. This can be explained in two ways.

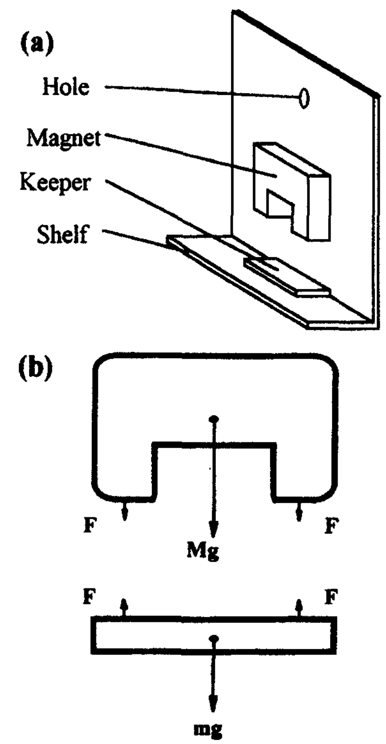

Fig. 1. (a) Magnet, plastic holder, and keeper before they are dropped. (b) Forces on magnet and keeper in free fall.

1. In free fall, the effect is to turn off gravity. Thus the keeper has no weight and is easily pulled toward the magnet.

2. The force of gravity is still acting as shown in Fig. 1(b). The magnet's acceleration is greater than g because the keeper is pulling it down. The keeper's acceleration is less than g because the magnet is pulling it up. Thus the magnet catches up to the keeper as they are falling.

Free-fall activity 2: Holed magnets on a horizontal rod. See Fig. 2(a). A horizontal rod goes through two holed

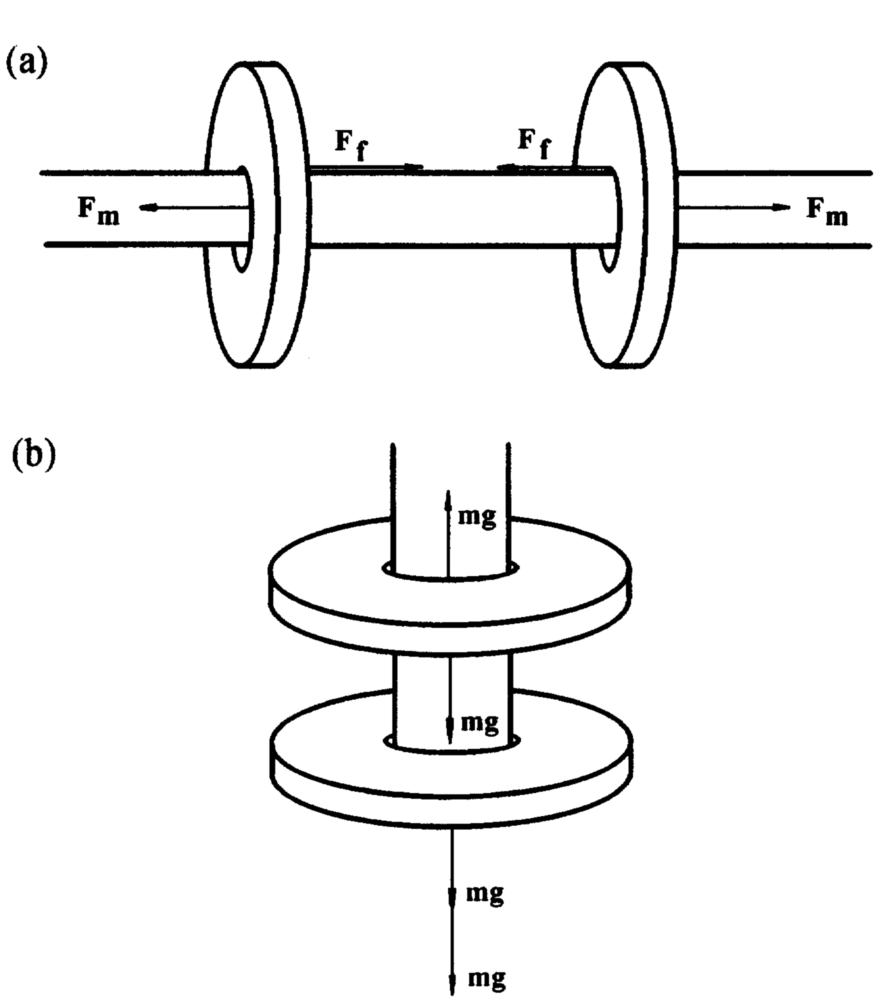

Fig. 2. (a) Horizontal forces on magnets on horizontal rod before it is dropped. (b) Forces on magnets on a vertical rod just after it is dropped.

magnets that are oriented so that they repel each other. (The rod can be a ballpoint pen.) When the rod is horizontal, the frictional forces between magnets and pen keep them from flying apart. When the pen is dropped, remaining horizontal as it falls, the magnets fly off the ends of the pen because the frictional force has disappeared.

In Fig. 2(a), F_m is the repulsive force on each magnet. Friction, F_f, is present before the pen is dropped because of the normal force exerted by the pen to hold up the magnet. In free fall, there is no normal force because the magnet is not being held up. Thus there is no friction.

Free-fall activity 3: Holed magnets on a vertical rod. See Fig. 2(b). The rod is glued to a flat piece of plastic, and the magnets are lowered onto it. For simplicity, consider only two magnets. The upper magnet is levitated, repelled by the magnet below it. When the rod is dropped, we can explain the result in two ways.

1. In free fall, gravity is turned off, in effect. Thus the magnets have no weight and are pushed apart.

2. Gravity is acting as shown in Fig. 2(b). Then the *top* magnet's acceleration is initially *zero*, because the magnets are still the same distance apart, and thus the lower magnet still pushes up on the higher magnet with a force of mg. If we neglect the mass of the holder, the *lower* magnets's initial acceleration is $2g$ because the total force on it is $2mg$ (the sum of the downward force of gravity and the downward force mg still exerted by the upper magnet).

Consequently, the magnets spread apart as they fall; the upper magnet appears to jump off the pen, landing on the table beside the pen. Repeat with three or four magnets. How many "jump" off the pen? Does any magnet actually move upward as the pencil is falling? (You can check with a video camera; replay on a four-head VCR that can display a single frame clearly. That takes us from the one-dollar class, but you might be able to borrow what you need from the custodian.)

Falling Slinky™. Hold a small ($1.95) Slinky by one end; let the other end hang down and come to rest. Now let go. As the spring toy starts to fall, will the bottom go down, go up, or remain at rest for a perceptible length of time? Try it and see.

Conservation of Energy and Momentum

Elastic collision 1: Small ball bouncing on large ball. Here are some hints on the physics involved in a well-known stunt. Hold a tennis ball above a table top, and hold a Ping-Pong™ ball so it rests directly on top of the tennis ball. Drop the two balls together; the Ping-Pong ball may rebound to the ceiling. (WARNING: This could be hazardous if the balls are misaligned; somebody could be hit in the eye.)[4]

The Ping-Pong ball gained kinetic energy when it bounced. Where did this energy come from? If you watched closely, you saw that it came from the tennis ball. The result can be analyzed by the conservation of momentum and energy. Let us assume that there is a tiny gap between the two balls. When the tennis ball hits the table, it reverses direction before the smaller ball reverses. Thus we can say that there is a collision between the tennis ball going upward with speed v and the Ping-Pong ball coming downward with speed v. If the Ping-Pong ball has mass m and the tennis ball has mass M, the momentum conservation equation is

$$-mv + Mv = mv_p + Mv_t \qquad (1)$$

where v_p is the speed of the Ping-Pong ball after the collision, and v_t is the speed of the tennis ball after the collision.

We could now write the energy conservation equation and find the ratio of v_p to v, but there is an easier way. When a collision is perfectly elastic, the balls separate as fast as they came together. The speed of separation is $v_p - v_t$, and they came together with a relative speed of $2v$. Therefore $2v = v_p - v_t$. Eliminating v_t by combining this equation with the momentum conservation equation, we find that

$$v_p = \frac{3M - m}{M + m} v \qquad (2)$$

Thus, for example, if the tennis ball's mass is nine times the Ping-Pong ball's mass, and the collision is perfectly elastic, then

$$v_p/v = (27m - m)/(9m + m) = 2.6 \quad (3)$$

and the Ping-Pong ball's final speed is 2.6 times its initial speed. This means that its kinetic energy is multiplied by 2.6^2 in the collision. It would therefore rise to 6.8 times its original height (relative to the point where it rebounded).

It is not hard to verify that these results are consistent with conservation of kinetic energy. The total kinetic energy just after the rebound is $m(2.6v)^2/2 + 9m(0.6v)^2/2 = 5mv^2$, the same as it was just before the rebound (when the total mass of $10m$ had a speed of v).

Elastic collision 2: Non-bouncing Super Ball™. In the above setup replace the tennis ball by a Super Ball whose mass is three times the mass of the Ping-Pong ball. In that case we find from Eq. (3) that

$$v_p/v = (9m - m)/(3m + m) = 2 \quad (4)$$

This means that the Ping-Pong ball rebounds with four times its initial kinetic energy, and you can easily verify that there is no energy left for the Super Ball! (In practice the Ping-Pong ball does not rebound exactly vertically, and you will see the Super Ball slowly rolling along the floor.)

Conservation of Angular Momentum

Bottle and pendulum (carnival scam). A pendulum is set up so that the bob nearly reaches the floor at its lowest point. It is then pulled aside, and a thin bottle is placed directly at this lowest (equilibrium) point. Challenge students to release the bob in such a way that it will miss the bottle only once, then come back and hit it. Of course if you simply release the pendulum, it will knock over the bottle. If you give the pendulum a sideways push when you release it, you can make it miss the bottle, but the *law of conservation of angular momentum* says that in that case it will continue to miss the bottle.

The angular momentum of a small object is related to a given axis. It is defined as the product of two quantities: the distance from the given axis, and the component of the momentum that is perpendicular to this distance. The horizontal component of the force on the pendulum bob is always directed toward the axis. The angular momentum cannot be changed by such a force.

If the swinging bob misses the equilibrium point (which lies on the axis), then its angular momentum will always make it miss, until frictional forces (which are not directed toward the axis) can slow it down and thus reduce its angular momentum sufficiently. There is little chance that this will happen between the first and second swings of the pendulum.

What is the *scam*? How does a carnival operator convince you that you could do this and win a prize? Simple; he succeeds in doing it himself! But he cheats; he sets up the bottle slightly off axis, so that the bob can pass by on one side of the axis, return on the other side of the axis, and hit the bottle.

***Voyager* simulation.** When a spacecraft's tape recorder is turned on, and a torque makes the motor spin, the reaction torque makes the spacecraft spin in the opposite direction. When this occurred on *Voyager* recently, photos were blurred by the motion, and NASA was faced with a mystery. The origin of the mystery can be demonstrated by a pocket tape recorder, as follows:

Find a round plastic bucket such as those used to hold cookies. Eat the cookies, then suspend the container from a ring stand by three threads, and you have a spacecraft. With a tape cassette in the recorder and the tape almost at its end, place the recorder on its side in your craft, activate "fast forward," hold the craft steady, then let go. When the automatic cutoff occurs, the tape and spools stop turning and their angular momentum is transferred to the entire craft, which is clearly seen to start rotating.

Another way to display this transfer is to balance the recorder on top of a watch glass resting on an overhead projector. If it is well-balanced when you press fast forward, you will see the entire tape recorder begin to turn when the cutoff occurs. It can rotate through an angle of 30° or more before friction stops it.

With perfect hindsight, how would you have avoided *Voyager's* problem? (See Ref. 5 for the answer.)

Remote-control car. The car is hung by a hook on the side, so that the axles are vertical, and it is brought to equilibrium. When the wheels begin to turn, the car turns in the opposite direction. You can see this same effect on the highway; when a car's brakes are applied, the car rotates and the front end goes down. What force causes the torque that makes the car rotate? Does a similar effect occur when a car accelerates forward?

Handgun. We have no hands-on activity with weapons, but anybody who watches TV has seen handguns or rifles being fired. You have probably noticed that the gun jerks upward as it is fired. Why? Does an actor in a shoot-em-up do this deliberately, just for show? Not at all. It happens because angular momentum is conserved. As you know, the explosion that propels the bullet forward also causes the gun to recoil. But the recoil force is directed along the gun barrel, which is above the center of mass of the gun and forearm. Thus the torque makes the gun go upward.

Would this effect occur if a blank were fired? Not to any perceptible degree. Only a small amount of gas, instead of a bullet, escapes in this case, so the recoil and the torque are much smaller.

Resonance

There are many reasons why resonance is important. It causes things to break. It allows you to rock a car out of a snowdrift. It can cause high tides and floods. Here are three challenge activities that dramatize the consequences of resonance.

Resonance challenge 1. Instead of breaking something, let us just knock something over. Three pendulums, all of different lengths, are suspended from a bent wire taken from a coat hanger and inserted in a wooden block (Fig. 3). A flat-ended pen stands up behind each pendulum. By touching nothing but the corner of the coat hanger, can you knock over one particular pen and leave the other pens standing upright?

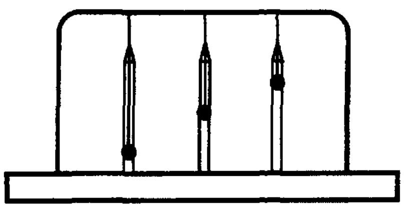

Fig. 3. Resonance apparatus: pendulums of different lengths, hanging from a bent coat hanger.

Solution: Move the coat hanger back and forth with a *very small amplitude*, watching the pendulum behind the target pen, then continue *at the resonant frequency of that pendulum*. That pendulum will swing with a steadily increasing amplitude, but because your movements are small, the other pendula make only small irregular motions.

Resonance challenge 2. Place a number of small magnets in an empty coffee can, hang the can from the ceiling, and challenge a student to grab it. The student cannot reach the can because she is standing behind a barrier, but she has a string, and there is a weak magnet on the other end of the string, sticking to the can by a weak magnetic attraction. Thus she can, in principle, pull the can toward herself, but if she pulls continuously, the magnet will fall off before she can grab the can.

Solution: Pull *periodically* at the resonant frequency of the can, pulling only when the can is moving *horizontally* toward you. This brings the can slightly closer at each period, so you can grab it. (If you pull when it is moving upward, you are trying to *lift* the can with your weak magnet. If you pull when it is moving away from you, you slow it down, your effort is wasted, and the magnet is likely to pop off.) The same principle applies to a car when it is stuck in a snowdrift or mud hole; after you first feel the car moving, you *push* only when the car is moving *away* from you.

Resonance challenge 3: Tides in a small pan of water. Tides are unusually high in bodies of water such as the Bay of Fundy because the water has a natural oscillation period that is about equal to the time between successive high tides. This effect can be simulated in a small rectangular pan (cost-free if you buy the cookies or pastry packaged in such a pan). Pour water into the pan and place it diagonally on two rollers and move the rollers back and forth at *a very small amplitude* and a very low frequency. You will see a wave flowing back and forth along the long axis of the pan. Gradually increasing the *frequency* of your movement will cause a sudden change; the waves will flow along the *short* axis instead of the long axis.

The resonant frequency equals the wave speed divided by the wavelength; waves that flow along the long axis have a wavelength that is equal to twice the *length* of the pan. Waves flowing along the short axis have a wavelength that is equal to twice the *width* of the pan. The wave speed equals $\sqrt{dg}$, where d is the depth of the water and g is the acceleration of gravity. Varying d can test this relation. (Note that this formula is non-dispersive; the speed is independent of frequency. This condition holds for $\lambda > 2\pi d$.)

For a large-scale demonstration, place a fish tank diagonally on a rolling cart. Students enjoy seeing water splash on you while the cart barely moves. This effect is also seen in cups of hot coffee, but the analysis is more sophisticated in that case.

Acknowledgments

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References

1. J.D. McGervey, *Bull. Am. Phys. Soc.* **39**, 1142 (1994).
2. A quantitative version can be done with a bathroom scale and a video camera (unfortunately taking it out of the dollar-a-hand category). See "The bathroom scale accelerometer," Joe Pizzo, AAPT *Announcer* **24**, 100 (July 1994).
3. Arnold B. Arons, *A Guide to Introductory Physics Teaching* (Wiley, New York, 1990), p. 31.
4. W.R. Mellen, *Phys. Teach.* **33**, 56 (1995) provides a way to avoid this hazard.
5. Use two identical tape machines with tapes rotating in opposite directions, and turn them on or off simultaneously.