SCOPE, SEQUENCE, and COORDINATION

A National Curriculum Project for High School Science Education

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National Science Teachers Association

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National Science Education Standard—Physical Science
Conservation of Energy and the Increase in Disorder

a. The total energy of the universe is constant. Energy can be transferred by collisions in chemical or nuclear reactions, by light waves and other radiations, and in many other ways. However, it can never be created or destroyed. As these transfers occur, the matter involved becomes steadily less ordered. All energy can be considered either kinetic energy, which is the energy of motion; potential energy, which depends on relative position; or energy contained by a field, such as electromagnetic waves.

b. Everything tends to become less organized and less orderly over time. Thus, in all energy transfers, the overall effect is that the energy is spread out uniformly. Examples are the transfer of energy from hotter to cooler objects by conduction, radiation, or convection, and the warming of our surroundings when we burn fuels.

Teacher Materials

Learning Sequence Item:

1026

Qualitative Examples of Conservation of Mechanical Energy

January 1997
Adapted by: Stephen Druger

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a. Work: Kinetic, Potential, and Field Energies. Simple machines should be understood in the context of work input equaling work output as one of the simplest applications of the law of conservation of mechanical energy. Students should then be able to solve problems involving kinetic and potential energies of simple systems and to use the law of conservation of mechanical energy to examine transformations between kinetic and potential energies for systems like a pendulum, a compressed spring, a roller coaster, or a planet in an elliptical orbit around a star. Students should begin to see energy as an accounting system and be able to describe exchanges of mechanical energy qualitatively in "Rube Goldberg" type devices (*Physics, A Framework for High School Science Education, p. 29).*

b. Heat, Transfer of Thermal Energy, Second Law of Thermodynamics. The mechanical equivalent of heat should be determined, allowing students to make the connection between calories and joules, and more importantly, between work and heat (*Physics, A Framework for High School Science Education, p. 31).*

Contents

This micro-unit was adapted by **Stephen Druger** (Northwestern University, Evanston, Ill.)

1026

Learning Sequence

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Science as Inquiry	Science and Technology	Science in Personal and Social Perspectives	History and Nature of Science
The Principle of the Lever **Activity 1** Block and Tackle **Activity 2** On the Fast Track **Activity 3** Getting into the Spring of Things **Activity 4** The Rube Goldberg Invention Kit **Activity 5** And What Did All That Work Accomplish? **Activity 6** Moving a Boulder **Assessment 1** The Mystery Gear Box **Assessment 2** A Weight-Lifting Machine **Assessment 3** How High Can a Super Ball Bounce? **Assessment 4** Downhill Coasting **Assessment 5** The Speed of a Pendulum **Assessment 6**	The Rube Goldberg Invention Kit **Activity 5**		

Suggested Sequence of Events

Event #1

Lab Activity

1. The Principle of the Lever (30 minutes)

Event #2

Lab Activity

2. Block and Tackle (40 minutes)

Event #3

Lab Activity

3. On the Fast Track (35 minutes)

Event #4

Lab Activity

4. Getting into the Spring of Things (55 minutes)

Event #5

Lab Activity

5. The Rube Goldberg Invention Kit (55 minutes)

Event #6

Lab Activity

6. And What Did All That Work Accomplish? (60 minutes)

Event #5

Readings from Science as Inquiry, Science and Technology, Science in Personal and Social Perspectives, and History and Nature of Science

Readings to be added.

Assessment items are at the back of this volume.

Assessment Recommendations

This teacher materials packet contains a few items suggested for classroom assessment. Often, three types of items are included. Some have been tested and reviewed, but not all.

1. Multiple-choice questions accompanied by short essays, called justification, that allow teachers to find out if students really understand their selections on the multiple choice.

2. Open-ended questions asking for essay responses.

3. Suggestions for performance tasks, usually including laboratory work, questions to be answered, data to be graphed and processed, and inferences to be made. Some tasks include proposals for student design of such tasks. These may sometimes closely resemble a good laboratory task, since the best types of laboratories are assessing student skills and performance at all times. Special assessment tasks will not be needed if measures such as questions, tabulations, graphs, calculations, etc., are incorporated into regular lab activities.

Teachers are encouraged to make changes in these items to suit their own classroom situations and to develop further items of their own, hopefully finding inspiration in the models we have provided. We hope you may consider adding your best items to our pool. We also will be very pleased to hear of proposed revisions to our items when you think they are needed.

Science as Inquiry

The Principle of the Lever

How does this simple machine make work easier?

Overview:

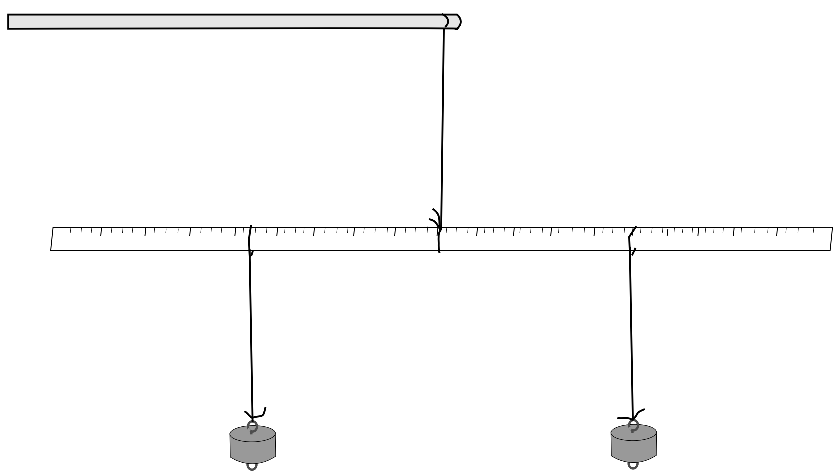
This activity leads students to find the relation between the force applied perpendicular to a lever at a given location and the force that results at a given distance on the other side of the lever's point of support. In addition, students are led to consider a practical use of a simple machine of this sort.

Materials:

Per lab group:

string
tape
meter stick
masses (identical, 30 g each), 6
(or two 30-g masses and additional masses to total 60 g and 90 g)
horizontal support bar mounted on ring stand (optional,
if no convenient alternative support is available)

Procedure:



Have students hang two equal masses (about 30 g each) from strings that are loosely looped at the ends of a meter stick suspended from a string at its midpoint. Tape may be used to hold the string fixed at the desired location. One of the masses should be temporarily secured in place at the 25-cm mark using a piece of tape. Students then slide the other mass to balance the stick horizontally, confirming that the two distances from the meter stick's point of support must be equal to balance the meter stick supporting the masses.

The mass at the fixed location is then increased to 60 g and students adjust the movable mass to balance the meter stick, finding that the mass must be twice as distant from the meter stick support as is the 60-g mass. Next students increase the fixed mass to 90 g. In this case both the 90-g and 30-g masses will need to be repositioned. They find that the 30-g mass must be three times as distant as the 90-g mass from the support string for the meter stick to balance.

It is recommended that students explore this phenomenon further by placing a prism or other appropriately shaped object *under* the meter stick to serve as a support and placing the masses *on top of* the stick. They then repeat the measurements using 30-g and 60-g masses.

Background:

Pushing down on the lever at a distance d_1 from its point of support causes the lever to exert a force at a second location that is inversely proportional to its distance d_2 from the fulcrum (or point of support), so that the corresponding forces satisfy the relation $F_1 d_1 = F_2 d_2$.

This relation follows from Newton's laws in that the torque produced by the force F_1 applied perpendicular to the meter stick is simply $F_1 d_1$, the product of the force and the moment arm d_1. For the meter stick to balance, the two torques applied at different points and tending to rotate the meter stick in opposite directions must be equal.

The same overall conclusion follows when the work done is considered. If the meter stick is rotated slightly by exerting a force at a certain location, a location three times as far from the support moves three times the same distance. Conservation of energy requires that the work the second force does in moving an object equal the work done by the first force in moving the stick. Since the distance through which the object moves under the influence of the force is three times as great, and since the work (given by the force times the distance the location on the meter stick moves) is the same, the force at the more distant location must be one third as great.

In this activity, each force is the weight of the mass hanging at that point. If the two masses are equal, the relation $F_1 d_1 = F_2 d_2$ implies they must be at equal distances from the support of the meter stick to balance it. Similarly, a force three times as large on one side compared with the other must be at a distance from the point of support that is one third as great as the other for the meter stick to balance.

Hanging masses from the meter stick rather than placing the masses on top leaves no question about where each force is exerted. When repeating the measurements with the masses placed on top, students are likely to ask precisely where on the stick to locate the point of application of each force. The answer is that it can, in effect, be taken to be directly beneath the center of the mass.

The principle of the lever finds numerous practical applications. A pair of pliers, for example, is squeezed on its handles far from the pivot, compared with the location where the gripping force acts, so that the gripping force is much stronger than the force applied by hand. Similarly, students are likely to be well aware from their younger days that a heavier child can balance a lighter one on a seesaw if the heavier one sits closer to the axis of rotation of the seesaw.

Adapted from: none

Science as Inquiry

Block and Tackle

Energy and work relations for a simple machine

Overview:

Here students examine the energy changes and work done in lifting an object through the same distance using two different pulley arrangements. The two arrangements require different applied forces pulling the supporting string through different distances to lift a mass to the same height. The force multiplied by the distance over which it acts is the same in both cases, thus providing an empirical justification for regarding the mechanical work done to be the force multiplied by the distance through which the object it acts upon moves. Students also see how a simple machine can be used to lift heavy objects with less force than would otherwise be required, even with the same work done.

Materials:

Per lab group:

horizontal bar mounted on ring stand
spring balance
meter stick
single pulley
double pulley
string
mass (compatible with range of spring balance)

Procedure:

If the spring balance is adjustable, it should be adjusted to read zero when held upside down (the position in which it will be used); otherwise, the reading in this position should be noted and used to correct other force measurements made.

Have students tie the mass to one end of a string and hang the string over a pulley supported by bar and ring stand. The spring balance is then attached to the other end, as shown in Figure 1. Students observe that the force exerted by the spring balance to move the mass slowly through a distance of 10 cm is equal to the weight of the hanging mass.

Students next measure the force that must be applied by the spring balance to accomplish the same elevation of the mass using the double pulley arrangement in Figure 2. They again measure the distance through which the spring balance must be moved to lift the mass 10 cm. They find that the distance the spring balance

Figure 1

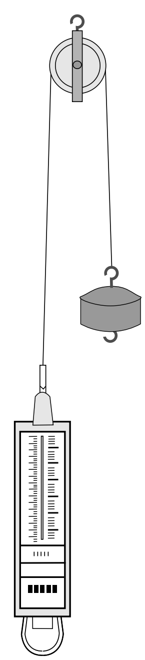
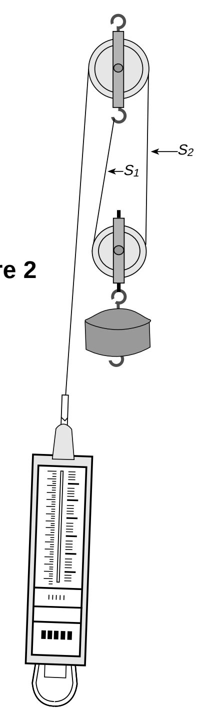


Figure 2



moved doubled and the force on the spring balance was reduced to half, so that the force multiplied by the distance the spring balance moved was the same as that for the one-pulley arrangement. This corresponds to the amount of work done in lifting the mass hanging from the pulley.

Background:

In Figure 1 the pulley merely changes the direction of the force exerted by the spring balance, so that the reading on the spring balance is the same as the force of gravity on the mass. (It can be seen that the pulley and the ring stand supporting it accomplish this by exerting a force upward on the string that is twice the weight of the mass the string supports.)

In the double-wheeled pulley arrangement in Figure 2, the mass moves the same distance that the spring balance moves. However, when the string is pulled a small distance half the change in the remaining length comes from shortening the length s_1 and half from shortening the length s_2, so that the mass is raised only half the distance traversed by the spring balance. Apart from friction, the same work had to be done in both pulley arrangements to lift the mass through the same specified distance to produce the same energy change. The work is equal to the force exerted by the spring balance times the distance it moved, so when the spring balance moved twice as far in the double-wheeled pulley arrangement, it had to exert half as much force to do the same work.

In this activity, it is intended that students observe that the force is half as great when the double-wheeled pulley is used but the distance required is twice as great. It follows that the force multiplied by the distance is the same as that for one pulley, consistent with that being the work done in lifting the mass to change its potential energy.

This alone is hardly definitive proof in itself that the change in energy is given by the average force multiplied by the distance. The expression for the kinetic energy, $\frac{1}{2}mv^2$ (with m the mass and v the speed of a moving particle), follows mathematically from Newton's second law, which then leads to the conclusion that the change in kinetic energy expressed in this way, when a particle is accelerated over a small distance by a force, is equal to the force multiplied by the component of displacement in the same direction.

Newton's laws also imply an energy conservation theorem—when the force is determined by a potential energy in an appropriate way, the change in kinetic plus potential energy is the work done by the applied forces. At the same time there are other kinds of energy than merely those dealt with by Newtonian mechanics, and so the law of energy conservation is even more general than the energy conservation theorem in mechanics. While this is not expected to be presented to students at this level, they might reasonably be expected to recognize that even though the work done is indeed the average force multiplied by the distance the object moves, the experiment is merely consistent with that result and does not in itself prove that to be the only possibility.

Adapted from: none

Science as Inquiry

On the Fast Track

If it rolls downhill, how far uphill does it roll back?

Overview:

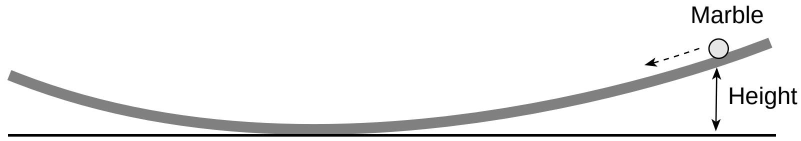
In this activity students examine the transformation between potential and kinetic energy as a marble rolls down a track and then back up the other side. They observe that energy is conserved and that the height attained by the marble on the far side of the track is no greater than the height at which it started rolling.

Materials:

Per lab group:
bendable plastic track
marble (large) or steel ball bearing
meter stick

Procedure:

Have students bend the plastic track into whatever shape might interest them, with the provision that it rises at both ends, preferably more sharply on one side than on the other. Nearby objects can be used as supports for the track. Students then release the marble from rest from various locations at one end of the track to roll down the track to the other side. They should record for each trial the location where the marble starts, where it momentarily stops to reverse its direction at the far end, and where it returns. Using a meter stick, they then measure the height at each location. In any one trial the height measurements at the near end of the track (the points of release and return) should be averaged to obtain a height corrected for frictional losses (on the assumption that the energy loss to friction is approximately the same in each direction traversed).



Background:

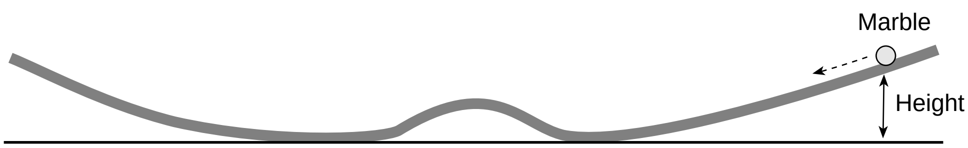
Apart from frictional losses to thermal energy, the total mechanical energy, given by the sum of the kinetic and gravitational potential energy in the present case, is constant. The kinetic energy cannot be negative. It is equal to zero when the marble starts and is equal to zero when the marble reaches the far end of the track. At the two extreme locations, the total energy is the potential energy alone, and in the absence of energy losses to friction would be the same. The weight of the marble is the force of gravity (given by the mass m multiplied by the gravitational acceleration g). The gravitational potential energy is the work that must be done in lifting the marble to its height *h*, which is then the force of gravity multiplied by the height and is therefore *mgh*. Since the potential energy of the marble is therefore proportional to its height and is equal when the marble is first released and when it stops to reverse its motion, it follows that the two heights are equal.

In practice, however, some of the mechanical energy is lost through friction and becomes thermal energy. Energy conservation then requires that the height attained when the marble stops to reverse direction will be a little less than the initial height and the return height will be still less. Assuming this same frictional energy loss to be about the same in both directions, the average of the initial and final heights at the near end of the track would be equal to the height attained at the stopping point at the far side of the track (since the gravitational potential energy is proportional to height, so equal loss of energy in each direction means an equal loss in maximum height attained each way).

When there is an elevated region separating two valleys in the track (which is proposed as a variation on this activity), in the absence of frictional energy losses, the kinetic energy at the highest point of the peak separating the two valleys is the difference between the initial total energy and the potential energy at the top of the peak. If the height of the peak is less than the initial height, the marble will still have positive kinetic energy $\frac{1}{2}mv^2$ at the top of the peak and, therefore, a nonzero speed with which it continues on into the next valley. But the kinetic energy can never be negative, and if the height of the peak is greater than the initial height, the potential energy the marble must have at the top of the peak is greater than the initial energy; hence, the marble cannot reach the summit. Instead, it stops and reverses its direction at a lower point, where its total energy is the potential energy it must have, leaving a kinetic energy of zero.

Variations:

The track can be bent so that the marble has a hill to climb in the middle before descending and finally rising on the far side. Students can then observe how the initial height determines the behavior of the marble, concluding that the initial height must be greater than that of the peak for the marble to reach the second valley, and that this can be explained in terms of energy conservation.



Adapted from: none

Teacher Sheet

Science as Inquiry

Getting into the Spring of Things

How far does an object move when pushed off a table by a spring?

Overview:

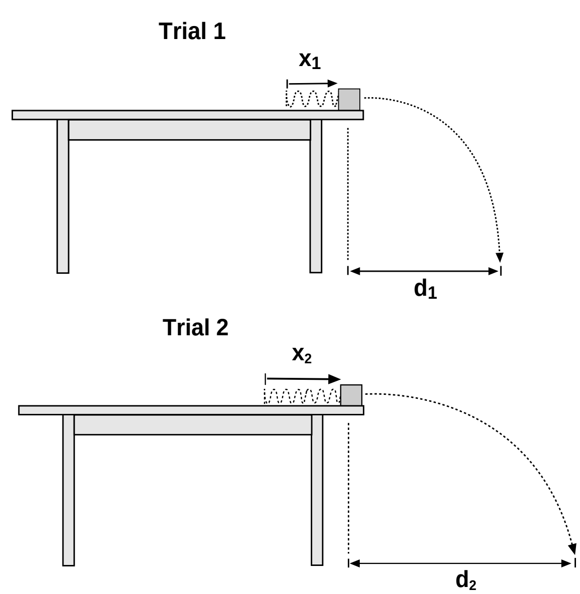
Using an adjustable spring with a release mechanism (for example, the plunger in a standard laboratory cart) students launch a wooden block horizontally from the edge of the work table using different choices of spring compression. They observe that the horizontal distance traversed before striking the floor is proportional to the compression of the spring. Students conclude that this relationship can be explained by the potential energy of the spring being converted into the kinetic energy of the block and by the kinetic energy being proportional to the square of the projectile's initial speed.

Materials:

Per lab group:

compressible spring with release mechanism
(such as a lab cart with spring plunger)
clamp
wooden block
meter stick
plumb line (string with fishing sinker weight attached)
chalk or washable marker

Procedure:



Have students clamp the spring to the top of the work table near its edge so that after being compressed and released it will propel the block forward off the edge of the table. The spring launcher could be the plunger of a ballistic cart clamped or held in position, or it could be a hacksaw blade clamped to the table (but bent only through small angles).

Using a plumb line, students mark off on the floor the position directly beneath the edge of the table. Have them measure the distance between the end of the spring when not compressed and the location when it is compressed. They then abruptly release the spring to knock the block off the table, recording the horizontal distance from the edge of the table to where the block hits the floor. They should repeat the process for different compressions of the spring.

Background:

The potential energy of compressing the spring is proportional to the square of the distance through which it is displaced and is given by $½kx^2$, where x is the distance of compression and k is a constant characteristic of the spring.

This result follows from Hooke's law, which states that the force exerted by the spring is proportional to the displacement x of the spring from its equilibrium position, as long as the spring is not compressed or stretched beyond its elastic limit. Given this proportionality, the average force being exerted throughout the motion of the spring after release should also be proportional to the initial displacement, where the average is over the distance it moves. In fact, this average should be the average of the initial and final forces, and therefore equal to $½kx$ in magnitude (for the initial value of the compression x), with the spring constant k characteristic of the particular spring used. The work done by the spring in accelerating the block is this average force times the distance over which it acts and is therefore $½kx^2$.

The potential energy of the spring is imparted as kinetic energy to the block, so that the initial kinetic energy of the block, given as half the mass times the square of the velocity, or $½mv^2$, is also equal to $½kx^2$. This equality means that the initial horizontal speed of the block is proportional to the compression of the spring. Since the block is propelled initially in a horizontal direction, and since the horizontal and vertical components of motion are independent, the time of fall is the same no matter what the compression of the spring. Therefore, the horizontal distance traversed, given by the horizontal speed multiplied by this same time of fall in all cases, is proportional to the initial horizontal speed v and therefore to the compression of the spring. This argument depends critically on the potential energy of the spring being transformed into kinetic energy of the block, and on the translational kinetic energy of a moving object being proportional to the square of its speed while the potential energy of the spring is proportional to the square of its displacement.

The expression for the kinetic energy arises naturally in mechanics from an energy conservation theorem implied by Newton's laws, rather than being merely a separate experimental result. This theorem states that the work done by a force in accelerating a particle is equal to the change in $½mv^2$. This can be seen without using calculus in the special case where the force is constant and the particle starts from rest.[1] The principle of energy conservation is more general than the energy conservation theorem in classical mechanics, however, in that it applies when other kinds of energy than considered above need to be included, an example being the electromagnetic energy of light propagating in a vacuum.

[1] For a constant applied force acting on a particle, the work done is simply the constant force multiplied by the distance. The force is the mass m multiplied by the acceleration a, so the work W is then this force $F = ma$ multiplied by the distance d, so $W = F \times d = mad$. But in this expression for work, multiplying the acceleration a by the time t over which it occurs gives the final speed v, and dividing the distance d by the same time gives the average speed, which is half the final speed v for constant acceleration starting from rest. So $W = mad$ is equivalent to $W = m(at)(d/t)$, which, in view of the meaning of at as the final speed v and d/t as half the final speed v, implies $W = ½mv^2$. This means that the work done in accelerating the particle is equal to the change in $½mv^2$, since $½mv^2$ started from zero.

Students are asked to observe empirically that the range of the ejected block in this experiment is proportional to the compression of the spring. They are led through the argument given above for why the energy of the spring should be proportional to the square of the distance through which the spring is compressed. From this they are led to conclude that in order to explain their experimental results, it was necessary for the kinetic energy to be proportional to the square of the speed. This then illustrates the quantitative character of the interchange from potential to kinetic energy.

Adapted from: none

Science as Inquiry/
Science and Technology

The Rube Goldberg Invention Kit

Build your own energy conservation machine

Overview:

Here students exercise their creativity in designing and building a Rube Goldberg device to accomplish the goal of lifting a mass at least 10 cm in the most complicated way possible. They also analyze the energy transformations in the process, learning some physics along the way.

Materials:

Per lab group:

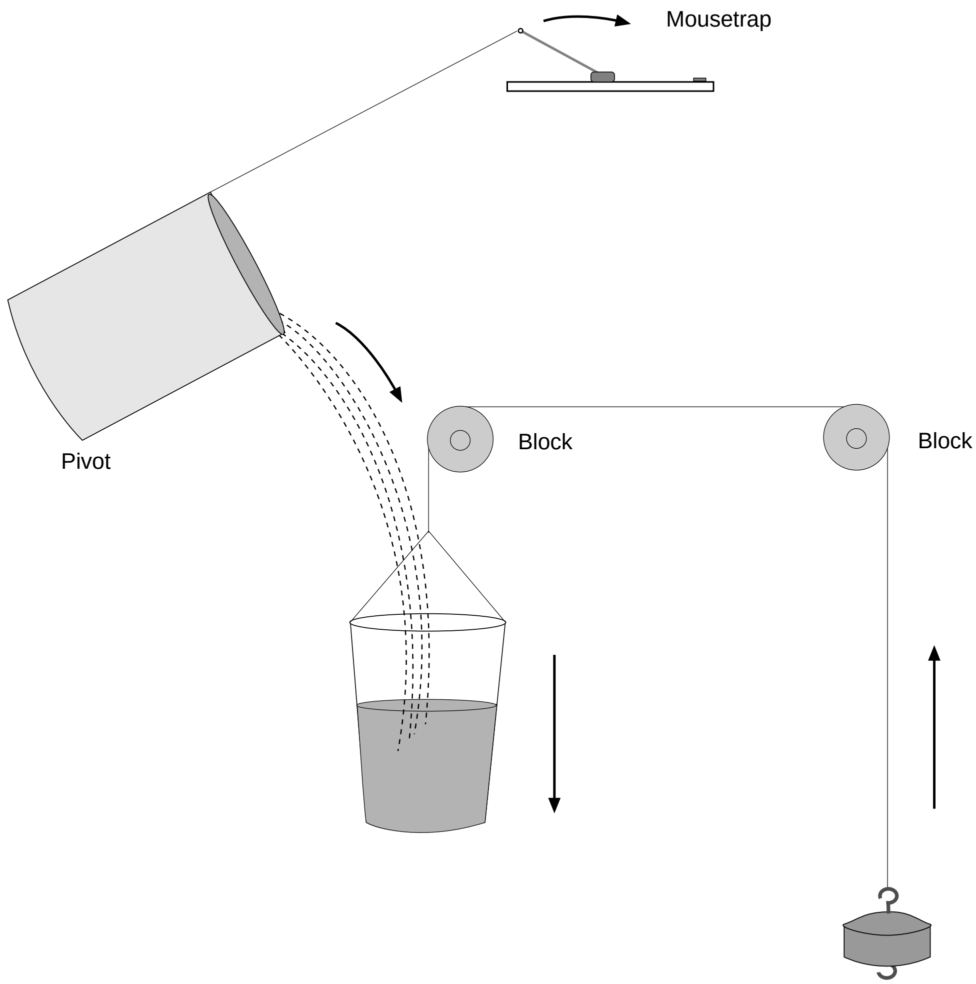
miscellaneous items to construct mechanical devices
e.g., wood blocks, scrap wood, tape, string, paper clips,
thread, cardboard, paper, sand, water glue, spools, cans,
Styrofoam® cups, nails, masses, mouse traps, springs, pulleys

Procedure:

This activity is an exercise in creativity as well as physics. Students are given a collection of assorted items and allowed reasonable use of other available equipment around the lab to invent ways to combine simple devices based on springs, levers, pulleys, water falling into cans, etc., so that merely pulling a string or touching a spring release will cause a weight to be lifted by at least 10 cm. They then analyze the source of energy in each step and the energy transformations that occur in each step.

Background:

A sample Rube Goldberg device is illustrated both here and in the Student Materials. In this case, potential energy has been stored in the spring of the mousetrap. When the trap is sprung, using a pencil or other safe means, some of the potential energy is converted into kinetic and ultimately thermal energy, and some of this energy does work to tip over the cup of water. The potential energy of the water at its initial height is converted into kinetic energy as it falls to fill the cup. Then some of its remaining potential energy is used to do work by lifting the weight. In addition, the momentum of the falling water makes the force on the receiving cup slightly greater than that calculated from the weight of the water in the cup alone. Therefore, some of the kinetic energy of the moving water is also recovered in lifting the mass, though most of it goes into thermal energy. The Rube Goldberg device proposed here would probably be considered to involve three steps.



This activity could be carried out as a class competition to see which group can design and construct the device with the largest number of steps, with perhaps a separate recognition for the most creative device. There should be a few rules, such as requiring that all winning entries actually be constructed and shown to work, and that all intermediate steps must occur without further human intervention after the initial step of pulling a string or touching a spring release. Since ambiguity is possible about what operations together constitute a single step in a process, and since a subjective opinion will be needed about which arrangement is the most creative, the teacher or an appointed committee of the class will have to serve as judge of the contest (with the judge's decision final, of course), or else some other alternative mechanism for choosing a winner will need to be prescribed beforehand.

Prizes too? Why not!

Adapted from: none

Science as Inquiry

What Did All That Work Accomplish?

Why there is an energy crisis

Overview:

Students repeatedly invert a cardboard mailing tube containing about 2 kg (about 1 lb) of lead shot, so that the lead shot is repeatedly lifted and allowed to fall 100 times. The temperature of the lead shot is measured before and after. A temperature increase of about 2 K (2 Celsius degrees) is typically observed, demonstrating that the mechanical work done on the system has been transformed into thermal energy.

Materials:

Per lab group:

cardboard mailing tube
lead shot, 2.2 kg
large, bulky book mailing envelope (or other comparable insulating material)
tape
scissors
cork or rubber stopper to fit tube, solid
cork or rubber stopper with thermometer mounted in it to fit tube

Procedure:

Have students weigh out 2.2 kg of lead shot and place them in the cardboard mailing tube. For best results, they should use some thermally insulating material, such as a large cushioned book mailing envelope cut and taped around the mailing tube. Before doing the experiment, students should measure the length of the tube, sealed with the solid stopper, and the average distance through which the shot fall when the tube is inverted top to bottom. (This length is the distance from the top layer of the shot to the opposite face of the stopper. This will have to be calculated by measuring the size of the stopper and how far it fits into the mailing tube.) The stopper with the thermometer mounted in it is then inserted into the tube and the tube carefully inverted to allow the shot to come in contact with the thermometer for an initial temperature measurement.

Replacing the stopper and thermometer with the solid stopper, students now quickly invert the tube top to bottom 100 times. They then measure the temperature of the lead shot again. They should find an increase in temperature of about 2 K.

Background:

The work done in lifting the shot repeatedly ends up increasing the thermal energy of the shot by increasing its temperature. On a microscopic level, the temperature increase corresponds to an increase in the atomic motion within the lead shot. The second law of thermodynamics implies that the thermal energy cannot be converted entirely back into macroscopic mechanical work with everything otherwise restored to exactly the same condition as before.

The work done in lifting the lead shot each time is its change in gravitational potential energy. Since the force required to lift the shot is its weight mg (for mass m of lead shot), the work done on the system for 100 inversions of the tube is 100 mgh. This is then the change in thermal energy. The change in temperature to which this corresponds is determined by the heat capacity of the lead shot. Specifically, the heat capacity (in units of calories per kg per Kelvin) multiplied by the mass times the change in temperature in Celsius degrees (or Kelvins) gives the heat in calories required to produce the temperature change. The essential point, however, is that this amount of heat measured in calories corresponds to an amount of work in Joules. Hence, the basic relation should be:

$$100\ mgh = mCDT$$

where the left side will be in units of Joules and the right side in units of calories. Here C is the heat capacity, whose listed values for lead range from 0.0308 cal g^{-1} K^{-1} to 0.0380 cal g^{-1} K^{-1}, and DT is the measured change in temperature. Using results of the measurement gives the number of Joules that are equivalent to 1 calorie, thereby determining the mechanical equivalent of heat.

Typical Answers to Student Questions

1. Describe what interchanges between kinetic and potential energy occur and their relation to work done on the lead shot during the process of inverting the tube until the point when the shot begin to fall.

Answer: Work is done on the lead shot by lifting them when inverting the tube, increasing their potential energy by moving them to a greater height. (Students might also observe that while the motion takes place there is also some increase in kinetic energy, requiring some additional work.)

2. How does the potential energy of the lead shot change as they fall? What happens to their kinetic and potential energies and to their total energy during this process up to the point where the shot are about to hit the bottom of the container?

Answer: When the shot are falling, potential energy is being converted into kinetic energy as the shot accelerate. The total energy stays the same.

3. What change did you observe in the lead shot after inverting the tube 100 times?

Answer: Students should describe the increase in temperature observed (typically about 2 Celsius degrees).

4. Work has been done on the system, but the lead shot are, in the end, located about where they were at the beginning. What do your results suggest has happened to the energy?

Answer: The energy was changed into a form that increased the temperature of the shot. (Students are likely to refer to this as changing the work into “heat.” That would not conform to the strictest use of the term “heat” in thermodynamics, which distinguishes between heat, work, and changes in internal energy, and defines heat as energy that flows because of a temperature difference. However, in the sense of meaning “thermal energy” or “energy that raises the temperature,” the idea conveyed would be correct. The term “thermal energy” is both descriptive and in better agreement with convention, however.)

5. Is this energy in a form where you could easily use it to move the lead shot back up to the top of the tube? Why or why not?

Answer: No. (A wide range of specific explanations from students seems likely. Students might describe how it would require constructing an engine of some sort and running it from the thermal energy to make a piston do work, not a trivial accomplishment. Or they might comment on how the kinetic energy of all the lead atoms moving together as one piece of lead shot has now been replaced by the energy of lead atoms moving randomly within the shot because their temperature is higher, making it hard to get them to all push in the same direction at the same time.)

6. It takes 0.038 calories of heat to raise the temperature of 1 g of lead 1 K (1K = 1 Celsius degree). From your data, calculate the work (in Joules) that was done on the system, then calculate the number of calories of heat that would have been needed to accomplish the same temperature change. By equating the two results, determine what amount of energy, according to your data, corresponds to 1 calorie of heat.

Answer: See discussion above for how students should analyze their data

7 and 8.

7. Are you doing work by walking a distance of 2 km on level ground? Explain the reasoning that leads you to your answer.

8. If your answer to question 7 was that walking 2 km on level ground really involves work, explain what happened to the energy in doing the work. If your conclusion is that it did not involve work, explain why it seems to take a lot of effort to walk that distance.

Answer: Actually, yes. One does do work by walking 2 km on level ground. We all know it really does take a lot of work exerting forces and moving objects through distances to do that much walking. Each time a person lifts his or her leg to take a step forward, work is done in the lifting, but the work is converted mostly into thermal energy that is useless for any further part of the walking when the leg is lowered at the end of the step. In addition, there are all sorts of internal losses to thermal energy merely in lifting one's foot to take a step and as other parts of the body move in balancing without the work being transformed into any recoverable form of energy, so it takes more in energy than just the mass times the change in height times g to lift one's foot to take each step.

(Because question 7 is suggestive of the same question for moving a block of ice or other idealized system without friction on level ground, some students are likely to answer "no" to question 7, but show that they really understand what is involved when they next respond to question 8.)

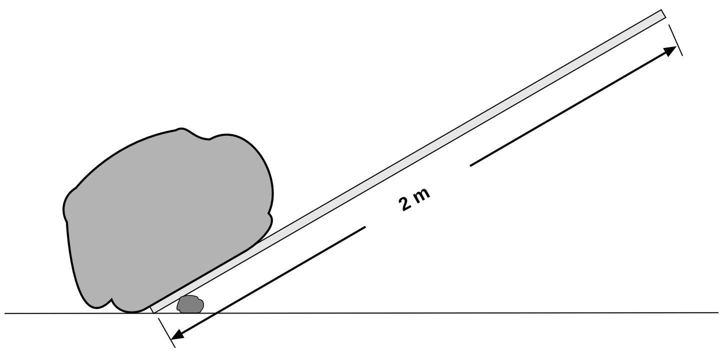
Adapted from: none

Science as Inquiry

Moving a Boulder

Item:

A student whose mass is 50 kg tries to move a heavy rock by wedging a steel shaft 2 m long under it, so that the shaft is pivoted on top of a smaller rock 2 cm from the end of the rod. How much force can the student exert at the end of the shaft, neglecting the weight of the steel shaft itself? Explain or show how you arrive at your answer.



Answer:

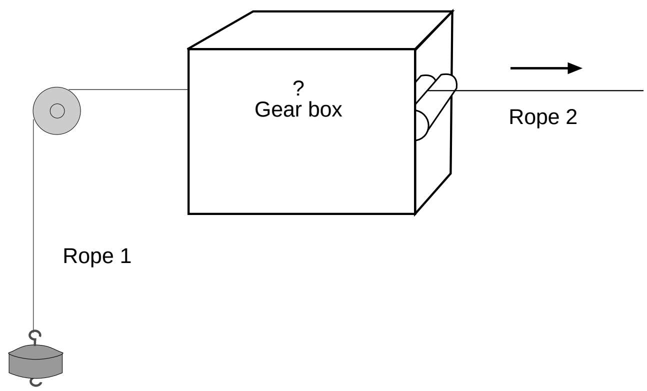
The maximum force the student can exert downward would be the student's own weight. This force is the mass of the student times the gravitational acceleration *g*, or $F = mg$ = (50 kg) × (9.8 m/s^2) = 490 N. The lever increases the force in inverse proportion to the distance of the mass from the small rock serving as a fulcrum. If the student is pushing down on the shaft at its end, which is 1.98 m (or 198 cm) from the fulcrum, this ratio is (198 cm)/(2 cm) = 99. So the maximum force exerted up on the large rock is 99 × 490 N = 49000 N (48510 N if students do not round off their final answer). Also, realistically the student would have to hold the steel shaft closer than at its end, so the force would be less.

Science as Inquiry

The Mystery Gear Box

Item:

An arrangement of gears, pulleys, and levers is put together so that each time a rope is pulled 1.0 m to turn a drum around which it is wound, a rope on the other side of the device is pulled in by 4.0 m. The mechanism is reversible, and the second rope can be pulled 4.0 m to pull back the first rope by 1.0 m.



Assume there is no loss of energy doing work against frictional forces and that there are no sources of energy involved except for the forces pulling on the ropes. If a force of 6.0 N is exerted on the first rope, what force would be exerted by the second rope and why?

Answer:

1.5 N. Since there are no energy sources and since no work is done against frictional forces, the work done on the system goes into energy that appears as work done by the force exerted by the second rope. Therefore, the force multiplied by the distance of motion is the same on both sides. Since the distance of motion is four times as great on the second side, and since the work equal to the force times the distance moved is the same, the force the second rope exerts in moving is one fourth as great and equal to 6.0 N/4 =1.5 N.

Science as Inquiry

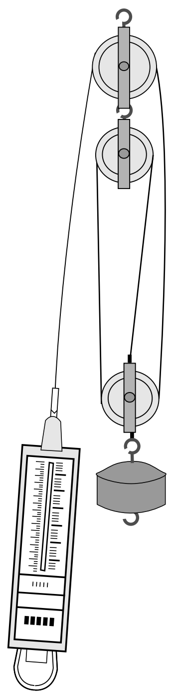
A Weight-Lifting Machine

Item:

A set of pulleys is arranged as shown. Disregarding forces from friction, the force you would have to exert to lift the 1-kg mass would be:

A. three times its weight
B. one third its weight
C. half its weight
D. the same as its weight
E. twice its weight

Explain your reasoning.



Answer:

B. When the string is pulled a short distance, one third of the length of the string pulled in comes from each of the vertical sections of string, so the mass is raised one third of the distance it would be if it were simply lifted directly. Since in the end we are lifting the mass the same distance, the string must be pulled three times as far as the mass is lifted. Since the work (force × distance) done in pulling the string three times as far is the same as that for lifting the mass directly, the force on the string must be one third the weight of the mass.

Science as Inquiry

How High Can a Super Ball Bounce?

Item:

Can a super ball bounce higher than the height from which it was dropped? Justify your answer, explaining what interchanges between different forms of energy occur in the process of dropping the ball and letting it bounce up.

Answer:

No. All the energy is potential energy when the ball is first released, when it stops to reverse its motion, and when it momentarily stops at its greatest bounce height. Gravitational potential energy increases with height. For its height to be greater, its total energy would have to be greater after the first bounce. This would violate energy conservation.

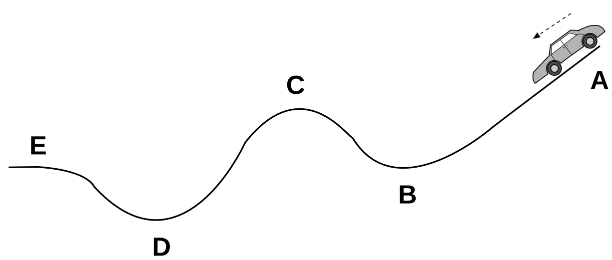
(In fact, the deformation of the ball on hitting the ground converts the kinetic energy into potential energy and thermal energy, with a further conversion to kinetic energy and thermal energy when it rebounds. The loss to thermal energy is large enough that it does not even come close to reaching its initial height. Students may perhaps refer to the activity involving the lead shot, in which mechanical energy was lost by being changed into thermal energy.)

Science as Inquiry

Downhill Coasting

Item:

A car coasts in neutral down a hilly road (generally a very dangerous way to drive!) as shown below. Assume that losses of energy doing work against frictional forces can be disregarded. At what locations is the speed of the car greatest and smallest, and why?



Answer:

The car is moving at its slowest speed at A and its fastest at D. At A the height is greatest, and therefore the gravitational potential energy is highest. Since the total energy is constant, this leaves the smallest kinetic energy for the motion of the car, resulting in the slowest speed. Similarly, at D the potential energy is lowest because the height is the least. That leaves the largest kinetic energy, corresponding to the greatest speed, at position D.

Science as Inquiry

The Speed of a Pendulum

Item:

A particular pendulum is constructed by hanging a mass of 1.0 kg from a string 2.0 m long. It is started swinging by pulling it to the side so that it is 1 cm higher than at its equilibrium position and then releasing it from rest. Determine how fast the pendulum is moving at its lowest point and explain your reasoning in obtaining your answer.

Answer:

The speed will be 0.44 m/s.

The total energy initially is entirely potential energy. This energy can be calculated as the work done in lifting the 1-kg mass. The work is the force (= mass × acceleration of gravity) times the distance the mass is lifted. At the lowest point, this has all been converted into kinetic energy, which is half the mass times the square of the speed of the pendulum.

Calculating the potential energy *mgh* gives for the initial energy:

$$(1 \text{ kg}) \times (9.8 \text{ m/s}^2) \times (0.01 \text{ m}) = 0.098 \text{ kg m}^2/\text{s}^2 = 0.098 \text{ J}$$

This is equal at the lowest point to the kinetic energy:

$$1/2\, mv^2 = 0.5 \times (1 \text{ kg}) \times v^2 = 0.098 \text{ kg m}^2/\text{s}^2$$

(Students should then multiply both sides by 2 and solve as shown.)

$$v^2 = 0.196 \text{ m}^2/\text{s}^2$$

$$v = 0.44 \text{ m/s}$$

(Note that the length of the string was not needed.)

Consumables

Item	Quantity (per lab group)	Event
chalk or washable marker	—	4
mailing envelope (bulky, to serve as insulation)	1	6
cardboard mailing tube	1	6
miscellaneous items to construct mechanical devices (e.g., wood blocks, scrap wood, tape, string, paper clips, thread, cardboard, paper, sand, water, glue, spools, cans, Styrofoam® cups, nails, masses, mouse traps, springs, pulleys, etc.	—	5
string	—	1, 2
tape	—	1, 6

Nonconsumables

Item	Quantity (per lab group)	Event
clamp	1	4
compressible spring with release mechanism (e.g., lab cart with spring plunger)	1	4
cork or rubber stopper (solid, to fit mailing tube)	1	6
cork or rubber stopper with thermometer inserted (to fit mailing tube)	1	6
double pulley	1	2
horizontal support bar mounted on ring stand	1	1, 2
lead shot	2.2 kg	6
marble (large) or steel ball bearing	1	3
mass	1	2
masses (identical), 30 g each	6	1
meter stick	1	1, 2, 3, 4
plastic track (flexible)	1 piece	3
plumb line (e.g., string with sinker attached)	1	4
scissors	1	6
single pulley	1	2
spring balance	1	2
wooden block	1	4

Key:
1. The Principle of the Lever
2. Block and Tackle
3. On the Fast Track
4. Getting into the Spring of Things
5. The Rube Goldberg Invention Kit
6. And What Did All That Work Accomplish?