Potential and Kinetic Energy: Roller Coasters
Teacher Version

This lab illustrates the type of energy conversions that are experienced on a roller coaster, and as a method of enhancing the students' understanding of that concept, they will create their own roller coasters to test out their ideas.

California Science Content Standards:
- **1. Motion and Forces: Newton's laws predict the motion of most objects.**
- **1l. Students know how to solve problems in circular motion by using the formula for centripetal acceleration in the following form: a=v2/r.
- **2. Conservation of Energy and Momentum: The laws of conservation of energy and momentum provide a way to predict and describe the movement of objects.**
- 2a. Students know how to calculate kinetic energy by using the formula: $E = (1/2) mv^2$.
- 2b. Students know how to calculate changes in gravitational potential energy near Earth's surface by using the formula (change in potential energy) = mgh (h is the change in the elevation).
- 2c. Students know how to solve problems involving conservation of energy in simple systems, such as falling objects.
- **2h. Students know how to solve problems involving conservation of energy in simple systems with various sources of potential energy, such as capacitors and springs.

Complete List of Materials (per group):
- 2 Foam Pipe Insulation Tubes (about 6' X 7/8' i.d. x 3/8' wall) cut in half (see instructions) which can be found at hardware stores:

- Masking Tape
- Marbles
- Large Wide Space- With available space to tape to.
- Metric Ruler/Measuring Tape
- Sharpie Pen

Key Concepts:
- **Energy** is the ability of a system or object to perform work. It exists in various forms.
- **Potential energy** is the energy an object has inside a force field due to its position. In the roller coaster's case, the potential energy comes from its height because the Earth's force of gravity is acting on it. Roller coasters are able to move their passengers very rapidly up and down the hills because the cars gain a large amount of potential energy from the very first hill.
- **Kinetic energy** is mechanical energy that is due to motion of an object.

- **Thermal energy** is energy due to the heat of a system or object. Energy can be converted to heat through frictional dissipation.
- **Friction**, or frictional dissipation, is a phenomenon in which mechanically *useful* energy, such as the motion of the roller coaster, is converted to mechanically *useless* energy, such as heat or sound. Friction acts on all moving objects, and it is the reason that a ball rolled across an open space will eventually slow down and stop.
- **"Conservation of Energy"** is a fundamental principle that energy cannot be created or destroyed. Rather, it is transferred between different forms, such as those described above.

Preparation and Lab Notes:
- Cut 2 pieces of foam insulation along the sides using scissors. **(Note: There may be already one side outlined for cutting).** Cut the foam insulation evenly in half.
- In order to minimize the amount of energy loss due to friction in this lab, it is necessary to construct hills that are taut rather than floppy. *This is very important to the successful execution of this lab.* Taut hills can be made by applying a continuous upward "pull" on the top of each hill. Similarly, the initial downward ramp can avoid "floppiness" by taping the first part of it flush against the wall. Taping the structure at multiple points to the floor or objects such as chair legs is very helpful.
- The roller coaster course can be structurally maintained by taping the hills and loops to other objects in the classroom, such as chairs and tables. This will help with accurate height measurements for these obstacles.

Introductory Lecture:
"Energy" is a term that is ubiquitous in everyday conversation, but it has a specific scientific definition. It is the ability of an object or system to do work. An example might be the kinetic energy that a moving roller coaster car has as it speedily travels on a downhill track. That energy can be used to do the "work" of carrying the car to the top of a subsequent hill. Similarly, the potential energy the car possesses at the top of that hill allows it to do the work of accelerating to a fast speed on the next downhill.

A fundamental principle of the physical world is that energy can neither be created nor destroyed. This principle is known as "conservation of energy". Still, energy can be transferred between different forms, as it is in the previous roller coaster example (kinetic to potential to

kinetic). The transferring of energy to different forms occurs continuously at all points in our world. Examples include the harnessing of thermal energy from combustion in a car engine to the mechanical energy that actually allows the car to move, or the transfer of electric energy to the mechanical rotation of a household dryer.
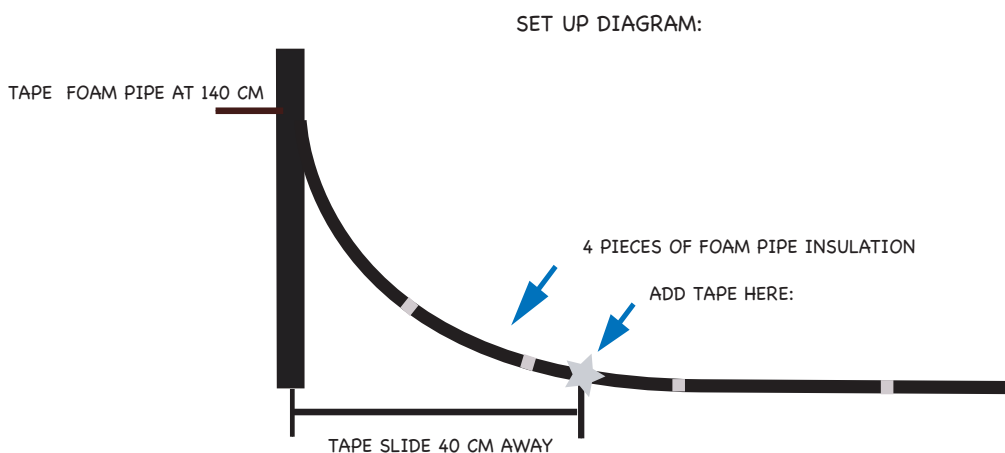
This lab will use the well-known paradigm of a roller coaster to illustrate conservation of energy. A typical model of a roller coaster is to start with the cars on top of a hill that is higher than any other hills on the track. This means that the potential energy of the cars at that point is greater than that at the top of any other hill. In an idealized world, that potential energy is transferred completely to kinetic energy as the cars speed down the first hill. Then, because any subsequent hills are shorter than the first, that initial kinetic energy is more than enough required to push the cars to the tops of those hills, as it is transferred to potential energy with the ascension of the cars up each hill.

This idealized description implies that a roller coaster could consist of a series of equally tall hills, and the cars would continue forever. That is obviously not the case in the real world. Intuition tells us that cars moving along a track will eventually slow down and stop, without any additional forces applied to them. This is due to *frictional dissipation*, in which the cars' motion along the track is converted to mechanically useless forms of energy, specifically heat and sound. Even though this process represents a loss of energy possessed by the cars, it is not a violation of the principle of conservation of energy. The energy simply moves from the cars to the surrounding environment. Frictional dissipation plays a prominent role in this lab, as it does with real roller coasters.

Part 1: Effects of Starting Height

1. You will have 4 pieces of foam insulation. To start, **tape 3 pieces of the foam insulation together**.

2. Tape the beginning of the rollercoaster at around **140 cm higher than the floor**.

3. Tape the slide down **40 cm away from the edge of the wall**.

(See **Diagram 1** for the set-up instructions 2-4)

SET UP DIAGRAM:

TAPE FOAM PIPE AT 140 CM

4 PIECES OF FOAM PIPE INSULATION

ADD TAPE HERE:

TAPE SLIDE 40 CM AWAY

Diagram 1

4. Have one partner form a hill, with its **peak located 1 m away horizontally from the starting point as shown in Diagram 2.** Do this by pulling up on the insulation to form the peak of the hill. It is helpful to tape the peak of the hill to a chair leg to hold it steady. As one partner holds it still, have the other partner **drop the marble from 60 cm vertical height**.

PREDICTION DIAGRAM:

START= 60 CM

PULL ON IT HERE!

TAPE HERE:40 CM

?

1 METER
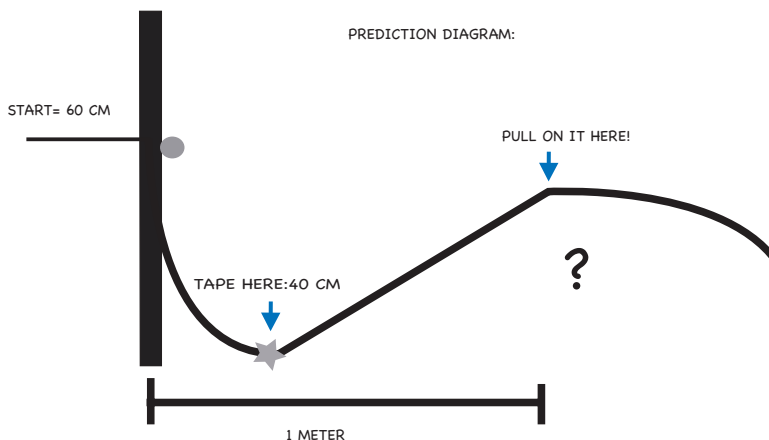
Diagram 2

(Note: The potential energy of the marble with mass m that starts at height h is equal to mgh. There is no kinetic energy initially if it starts at rest.)

QSA1. If there are no energy losses due to friction, what is the maximum hill height you expect it to climb?
60 cm

5. If the marble makes it over the hill, then raise the height and retry. If it does not roll over, lower the hill and retry. **Repeat this process until the maximum hill height is determined** (i.e. the marble nearly stops at the top of the hill.) *Record it in the table below.*

6. **Now drop the marble from 120 cm.** *Determine the maximum height of the hill and record it in the table below:*

Dropping Height / cm	Hill Height/ cm

QS1, QSA2. How does the increase in dropping height affect the maximum hill height?
The maximum hill height should increase with increased dropping height. It would double with this increase in the absence of friction, which is not the case.

QS2, QSA3. Is your dropping height larger than the height of the hill? Why do you think this is the case?
Frictional dissipation accounts for this energy loss.

Part 2: Energy Dissipation

1. Using the same maximum hill height as when you dropped the marble from 120 cm, **stretch the hill out further from the wall by 50 centimeters** (so the center of the hill is 150 centimeters from the wall). This should result in a more gradual slope of the hill up to the same height as in the previous test.

> *STUDENT ADVANCED VERSION ONLY*
> The energy dissipated from friction is due to a ***frictional force***, F_f. If an object travels a distance x, then the frictional dissipation of energy is equal to Force (F_f) × Distance (x)
>
> *QSA4. When considering frictional dissipation, do you expect the maximum hill height to be larger or smaller than the previous step?*
> *The maximum hill height will be smaller.*

2. If the marble makes it over the hill, then raise the height and retry. If it does not roll over, lower the hill and retry. **Repeat this process until the maximum hill height is determined** (i.e. the marble nearly stops at the top of the hill.) *Record it below:*
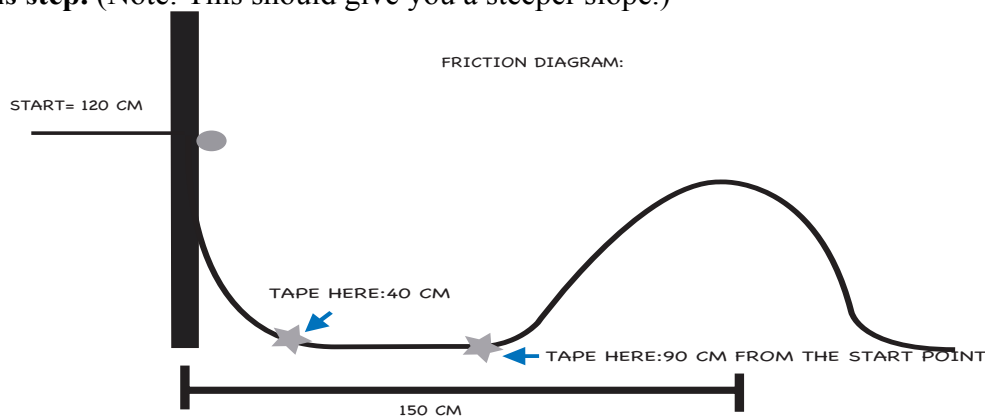
   Maximum hill height at 150 cm separation = _____

QS3. Is your maximum hill height at 150 cm separation larger or smaller than the maximum hill height at 100 cm separation? - Smaller

QS4. Why do you think this is the case?
The longer the marble is on the track, the more energy it will lose from the friction. This loss of energy will make the maximum hill height shorter on the longer the track.

3. Now, tape down the insulation **90 cm away from the starting point** as shown in the diagram below, but **keep the hill height the same as the maximum height determined in the previous step.** (Note: This should give you a steeper slope.)

FRICTION DIAGRAM:

START= 120 CM

TAPE HERE:40 CM

TAPE HERE:90 CM FROM THE START POINT

150 CM

Diagram 3

4. If the marble makes it over the hill, then raise the height and retry. If it does not roll over, lower the hill and retry. **Repeat this process until the maximum hill height is determined** (i.e. the marble nearly stops at the top of the hill.) *Record it below:*

Maximum steep hill height at 150 cm separation = _____

Another way energy is dissipated is through the flexibility of the foam, allowing the slide itself to absorb some energy as the marble rides up, and slightly pushes into, the side of the hill.

Q5. Was the maximum hill height different for the steep hill and the gradual hill?
As the steepness of the hill increases, the marble's velocity before the start of the hill is directed more into the track as opposed to along the track. It is this force directed perpendicularly to the hill that deforms the foam, dissipating the energy.

5. Now, **make a loop which, at its tallest point, is the same height as the value recorded directly above.** Have a partner hold it in place. See Diagram 4 below:

LOOP DIAGRAM:

START= 120 CM

TAPE HERE:40 CM

TAPE HERE:90 CM FROM THE START POINT

150 CM
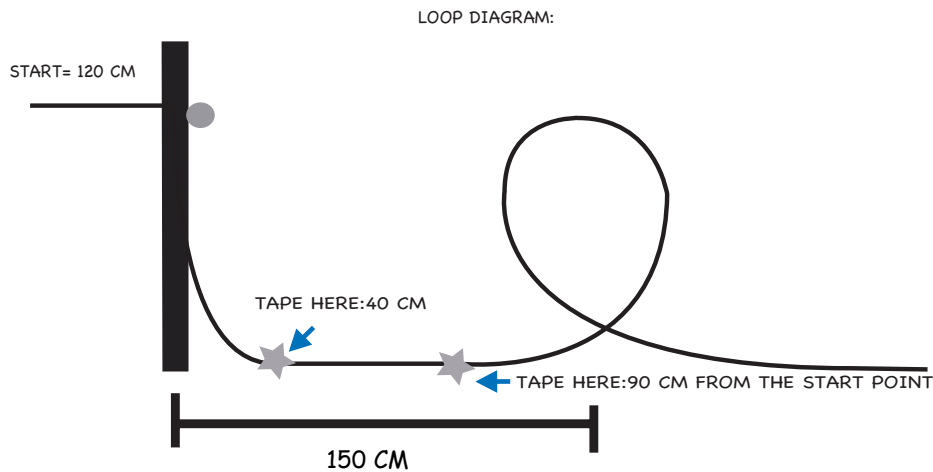
Diagram 4

6. **Drop the marble from 120 cm** and observe whether it completes the loop.

Q6. Does your marble complete the loop?
It should not.

Q7. Describe what you saw, if the marble did not complete the loop.
It should drop downward off the track at some point.

7. Try dropping the marble through a loop that is small enough for the marble to get through the highest point. If it does not complete the loop, then lower the loop size until it succeeds**.**

   Actual maximum loop height = _____

   If an object is to continue through a vertical loop, it is not enough for it to merely reach the highest point of the loop. It must actually have a minimum non-zero velocity (it must be moving) along the track at the top point in order to stay in contact with the loop. This velocity depends on the acceleration due to gravity, *g*, and the radius of the loop, *r*:

   $$v_{min} = \sqrt{gr}$$

8. **Calculate the radius of your loop.** Measure how high your loop is and divide by 2:

   Radius = _____

9. The acceleration due to gravity is 9.8 m/s^2 (980 cm/s^2). **Calculate the minimum velocity the marble must have to complete the loop:**

   Predicted minimum velocity = _____

7. Try dropping the marble through a loop that is small enough for the marble to get through the highest point. If it does not complete the loop, then lower the loop size until it succeeds**.**

   Actual maximum loop height = _____

   If an object is to continue through a vertical loop, it is not sufficient for it to merely reach the highest point of the loop. It must actually have a minimum non-zero velocity along the track at the top point in order to stay in contact with the loop. This is due to the effect of gravitational acceleration that pulls the object vertically downward and off the circular shape of the loop. The minimum velocity is determined by the following force balance:

   Centripetal Force is the total force acting on an object as it moves in a circle, with acceleration directed toward the center of the circle. If the object has velocity, *v*, around a circle of radius *r*, the corresponding centripetal force is given by:

   $$F_c = \frac{mv^2}{r}$$

This force must be equal to the sum of external forces acting on the object, which in our case is the gravitational force plus the force that the wall of the slide exerts on the marble, known as the **Normal Force.**

$$F_c$$

$$F_g + F_{normal} = F_c$$

$$mg + F_{normal} = \frac{mv^2}{r}$$

$$F_g + F_{normal}$$
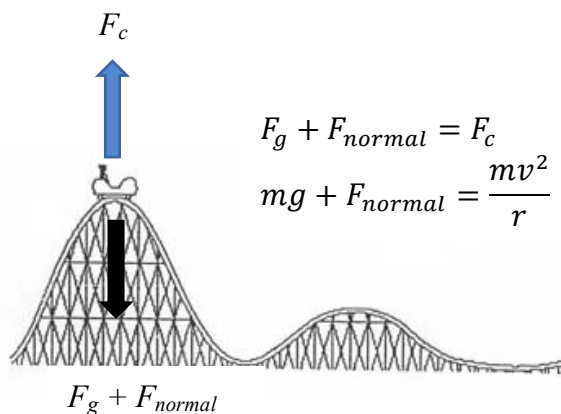
The normal force must be greater than zero (directed downward with gravity), at the top of the loop, if the marble is to stay on the track at that point. This means that the minimum velocity at the top of a loop is that of an object in a circle with a normal force equal to zero ($F_{normal} = 0$).

QSA8. Solve the force balance to write an expression for this minimum velocity in a loop:

$$v_{min} = \sqrt{gr}$$

8. The kinetic energy of a rolling marble is related to its velocity, v: $E_{kin} = \frac{1}{2}mv^2$

    At the top of the loop, the potential energy is given by:

$$E_{kin} = mgh = 2mgr$$

    Conservation of energy requires that the total energy at the top of the loop (kinetic and potential) is equal to the potential energy of the marble at the point of dropping.

$$Initial\ Energy\ (Point\ of\ Dropping) = Final\ Energy\ (Top\ of\ Loop)$$

QSA9. Write an expression for the maximum allowable height of a loop that a marble

can complete if dropped from a height h_1:

$$mgh_1 = mgh_2 + \frac{1}{2}mv^2$$

$$mgh_1 = mgh_2 + \frac{1}{2}mgr = mgh_2 + \frac{1}{4}mgh$$

$$h_1 = h_2 + \frac{1}{4}h_2$$

$$h_2 = \frac{4}{5}h_1$$

15. Acceleration due to gravity is 9.8 m/s^2 (980 cm/s^2). **Calculate the minimum velocity the marble must have to complete the loop:**

Predicted minimum velocity = _____

QSA10. How did the actual size of the loop compare to the predicted size? Why might they have been different?

The actual size of the loop is smaller than the predicted size, because of frictional dissipation.

Conceptual Questions

QS8, QSA11. Where is the kinetic energy greatest on the course of the roller coaster illustrated below? Where is the potential energy greatest? Label the diagram below:

The kinetic energy is greatest at the lowest point (2nd location), and the potential energy is greatest at the highest point (1st location).

LABEL:
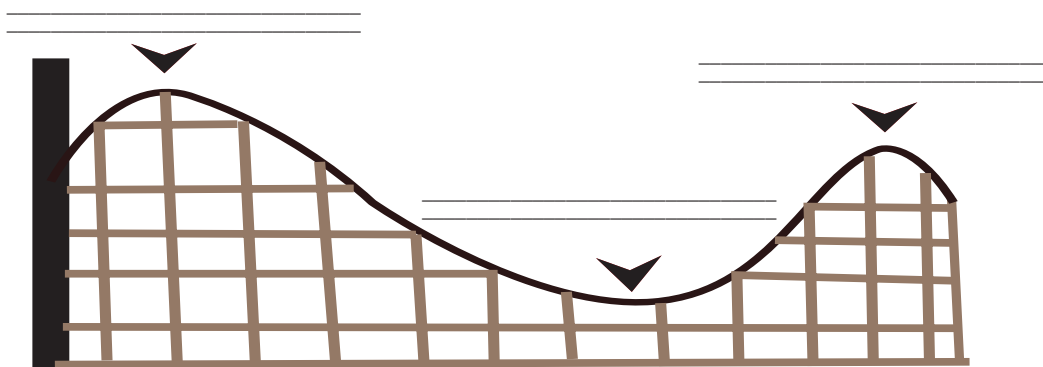
QSA12. If you increased the size of the marble, and therefore its mass, how would the potential and kinetic energy change?
Both the kinetic and potential energies would increase.

QS9, QSA13. Why is the first hill on all the roller coasters always the highest one?
In the absence of additional propelling forces along the track, it is impossible to achieve the initial height if there are any frictional losses, which is always the case in the real world.

Part 3: Competition - Build your own rollercoaster!

Now, you will have a competition to see who can make the best roller coaster! As you know, the most fun roller coasters are those that send the riders over the highest hills. The group who can make the most number of hills with the highest combined height (add up all the heights - hills need to touch the ground in between) on their rollercoaster will win!