

Potential and Kinetic Energy: Roller Coasters

Student Advanced Version

Key Concepts:

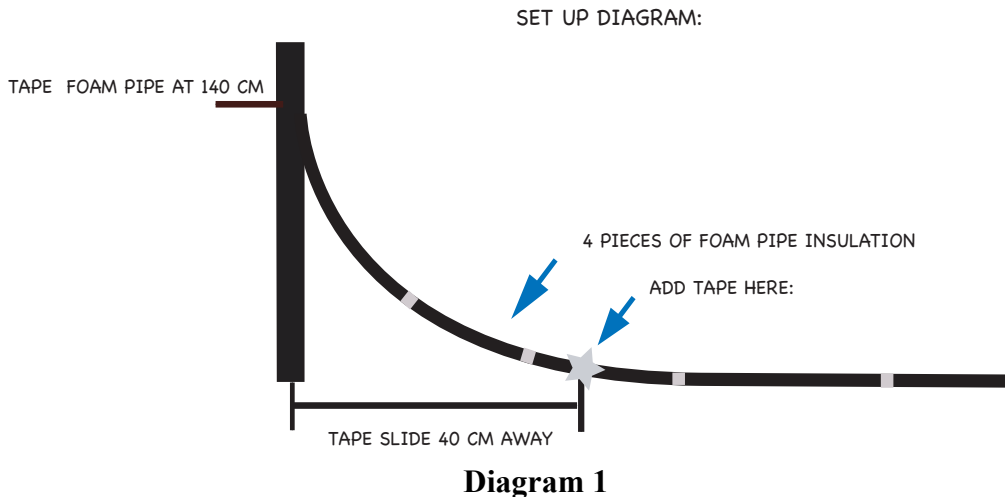
- **Energy** is the ability of a system or object to perform work. It exists in various forms.
- **Potential energy** is the energy an object has inside a force field due to its position. In the roller coaster's case, the potential energy comes from its height because the Earth's force of gravity is 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.



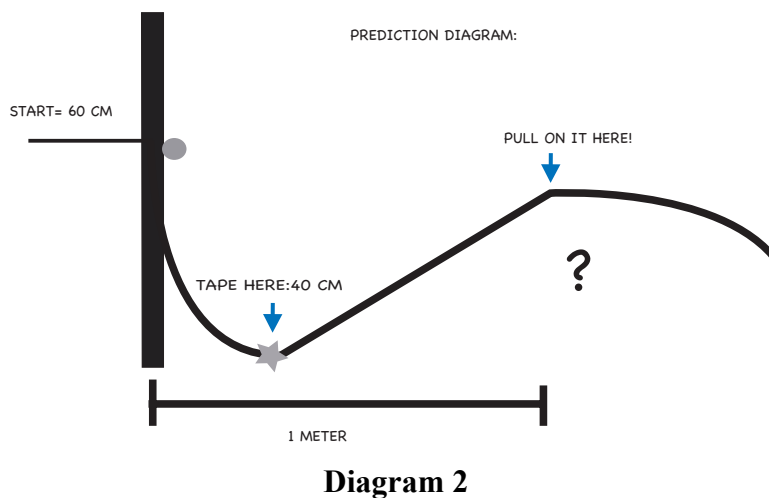
Part 1: Effects of Starting Height

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)



- 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**.



(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.)

Q1. If there are no energy losses due to friction, what is the maximum hill height you expect it to climb?

- 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 |
|----------------------|-----------------|
| | |
| | |
| | |
| | |

Q2. How does the increase in dropping height affect the maximum hill height?

Q3. Is your dropping height larger than the height of the hill? Why do you think this is the case?

Part 2: Energy Dissipation

- 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.

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) \times Distance (x)

Q4. When considering frictional dissipation, do you expect the maximum hill height to be larger or smaller than the previous step?

- 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 = _____

- 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.)

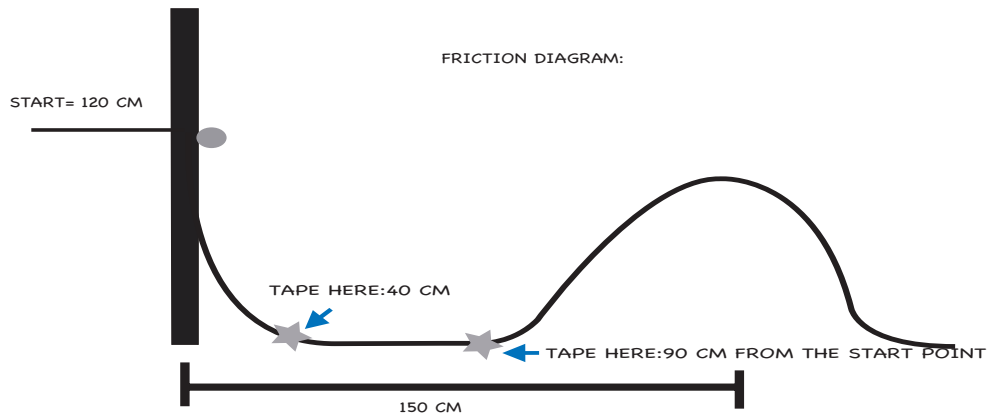


Diagram 3

- 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. Why do you think the maximum hill height was different for the steep hill and the gradual hill?

- 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:

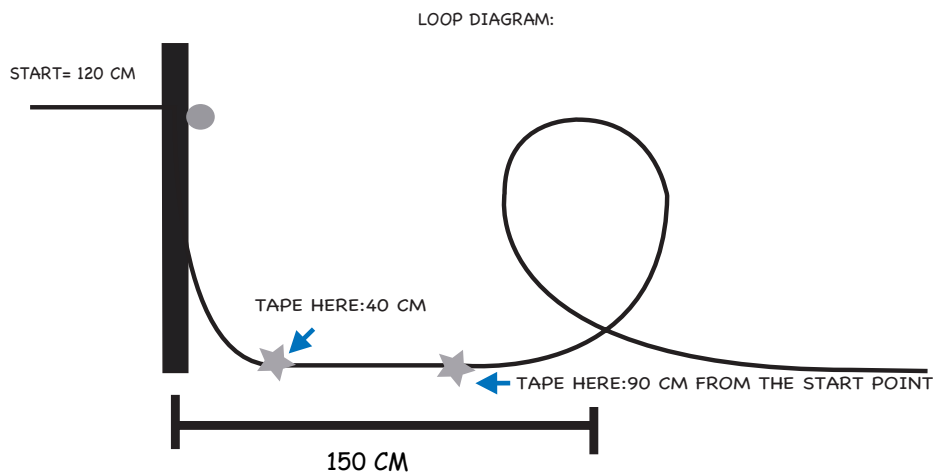


Diagram 4

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

Q6. Does your marble complete the loop?

Q7. Describe what you saw, if the marble did not complete the loop.

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.

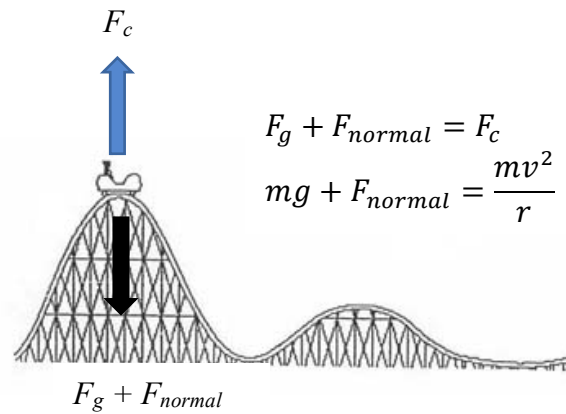
Actual maximum loop height = _____

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**.



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 ($F_{normal} = 0$).

Q8. Solve the force balance to write an expression for this minimum velocity in a loop:

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.

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

QSA9. Write an expression for the maximum allowable height of a loop that a marble can complete if dropped from a height h_1 :

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:**

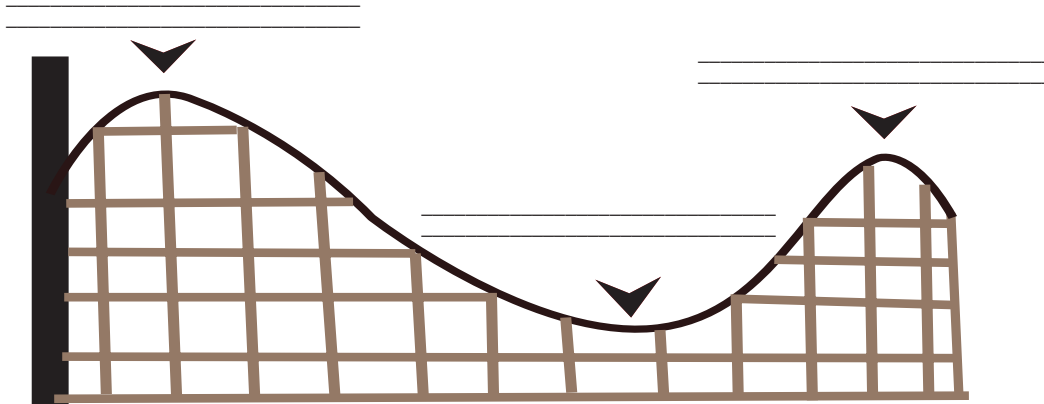
Predicted minimum velocity = _____

Q10. How did the actual size of the loop compare to the predicted size? Why might they have been different?

Conceptual Questions

Q11. 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:

LABEL:



Q12. If you increased the size of the marble, and therefore its mass, how would the potential and kinetic energy change?

Q13. Why is the first hill on all the roller coasters always the highest one?

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!