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APPS ON PHYSICS
Model of a Looping Coaster (Centripetal Force)

Reference: Simulation is available on Apps on Physics
Interface: Apps on physics >> Mechanics >> Model of a Looping Coaster (Centripetal Force)

Abstract:

This simulation demonstrates the motion of a rolling ball on a looping coaster. It focuses on centripetal force. A looping coaster is a type of roller coaster that features a vertical loop, where the riding vehicle completes a full 360-degree inversion. The model assumes a circular loop with straight inlet and outlet paths while neglecting factors such as friction and self-rotation.

Simulation is available at:
Apps on physics >> Mechanics >> Model of a Looping Coaster (Centripetal Force).

The simulation examines three key scenarios based on the initial height of the ball relative to the loop's radius:

1. If the initial height is less than or equal to the loop's radius, the ball oscillates like a pendulum.
2. If the height is between the radius and 2.5 times the radius, the ball rolls up the loop partially before falling back.
3. If the height exceeds 2.5 times the radius, the ball successfully completes the loop.

Using the control panel, you can adjust parameters such as the loop radius, initial height, and mass. The simulation also visualizes key forces, including centripetal, gravitational, and contact forces. It highlights the fundamental conditions for completing circular motion, such as maintaining sufficient speed at the loop's highest point, the relationship between initial height and velocity, and how the loop's radius affects the ball's success in completing the loop.

Formula used:

TITLE	FORMULA	DESCRIPTION
Centripetal Force (Fc)	$F_c = \frac{mv^2}{r}$	m = Mass, v = Velocity, r = Radius
Gravitational Force (Fg)	$F_g = mg$	m = Mass, g = Acceleration due to gravity
Minimum Speed to Complete the Loop (at top to avoid falling off)	$v_{\text{min}} = \sqrt{gr}$	g = Acceleration due to gravity, r = Radius
Velocity at the Top of the Loop	$v_{\text{top}} = \sqrt{2g(h-2r)}$	g = Acceleration due to gravity, h = Initial height, r = Radius

- The centripetal force formula helps you understand the force required to keep the ball on the track.

- The minimum speed at the top of the loop ensures the ball won’t fall off.

Key points: centripetal force, gravitational force, normal force, radius of loop, height of ball.

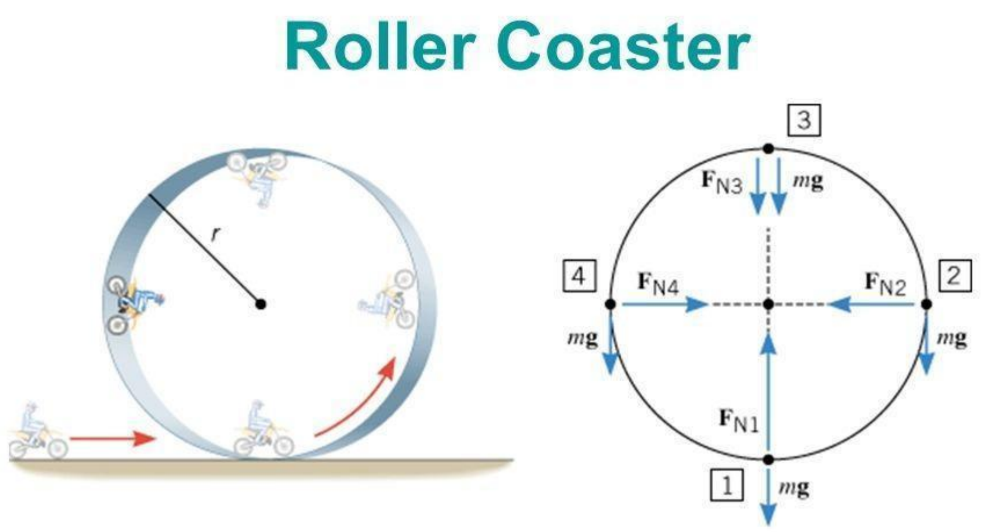
Aim of the Experiment:

The aim of this simulation is to demonstrate the motion and forces acting on a rolling ball in a looping coaster. It illustrates various behaviour based on the initial height and loop radius, explaining the conditions necessary for a safe and complete circular motion to prevent injuries to passengers.

Introduction:

This simulation models the motion of a rolling ball on a looping coaster, providing a detailed visualization of how different forces—gravitational, contact, tangential, and radial—affect the ball’s movement. By adjusting key parameters such as initial height, loop radius, gravitational acceleration, and mass, we can analyze how these factors influence the ball’s trajectory and the forces exerted throughout the loop.

The simulation also highlights the critical conditions required for achieving complete circular motion, ensuring that the ball maintains sufficient velocity to stay in contact with the track. Understanding these conditions helps in grasping the physics behind roller coasters and designing safer rides to prevent passenger injuries.



$$(1)\ F_{c1} = \frac{mv_1^2}{r} = F_{N1} - mg \qquad (3)\ F_{c3} = \frac{mv_3^2}{r} = F_{N3} + mg$$

$$(2)\ F_{c2} = \frac{mv_2^2}{r} = F_{N2} \qquad (4)\ F_{c4} = \frac{mv_4^2}{r} = F_{N4}$$

EXPLANATION:

This figure illustrates how different forces act at various points on the loop and demonstrates the role of centripetal force in achieving complete circular motion.

1. **Gravitational Force**: Pulls the ball downward, supplying the energy for its motion.
2. **Contact Force:** Keeps the ball in contact with the track, preventing it from falling off.
3. **Centripetal Force**: Directs the ball along the curved path of the loop, maintaining its circular motion.

To achieve complete circular motion, the ball must start from a height of at least 2.5 times the loop’s radius. This ensures sufficient conversion of potential energy into kinetic energy, providing the necessary speed to stay on the track at the highest point of the loop. If the ball's speed is too low, it will lose contact with the track and fall off, typically at the highest point, known as the "fall-down" region.

Procedure:

Step 1: Open the App: Open Apps on Physics, navigate to **Mechanics**. Click on **Model of a Looping Coaster (Centripetal Force**) (Image-1).
Step 2: Set Initial Parameters: Using the Control panel, Input values for the circle radius, initial height, gravitational acceleration, and mass of the ball (Image-2).
Step 3: Choose Simulation Speed: Select the desired speed for the simulation (5x or 50x slow motion) to observe the ball's motion more clearly.
Step 4: Start the Simulation: Begin the simulation to visualize the motion of the ball on the looping coaster.
Step 5: Observe Forces and Motion: Visualize how different forces like gravitational, contact, and centripetal forces act on the ball. Observe the ball's velocity and trajectory throughout the loop. Use clocks to track time, velocity, and force values to analyse the results. Determine whether the ball completes the loop safely or falls off the track **(Image-3)**.

CALCULATION:

Parameter	Value
Mass (m)	1 kg
Gravitational Acceleration (g)	9.8 m/s²
Initial Height (h)	0.8 m
Radius (r)	0.5 m

Step 1: Calculate Initial Energy (at height $h = 0.8\,m$)

Initial potential energy:

$$PE_{\text{initial}} = m \cdot g \cdot h$$

$$PE_{\text{initial}} = 1 \cdot 9.8 \cdot 0.8 = 7.84\,\text{J}$$

Initial kinetic energy $KE_{\text{initial}} = 0$ (since the ball is not moving initially).

Step 2: Calculate Energy at the Lowest Point (at $r = 0.5\,m$)

At the lowest point of the loop, the potential energy is zero, and all the energy is converted into kinetic energy.

The total mechanical energy remains constant, so:

$$E_{\text{initial}} = KE_{\text{final}}$$

$$KE = \frac{1}{2}mv^2$$

$$v = \sqrt{\frac{2 \cdot KE}{m}}$$

$$v = \sqrt{\frac{2 \cdot 7.84}{1}} = \sqrt{15.68} \approx 3.96\,\text{m/s}$$

RESULT:

TABLE-1:
CONSTANT HEIGHT & MASS, VARYING RADIUS

INITIAL HEIGHT (m)	MASS (kg)	RADIUS (m)	VELOCITY (m/s)		WEIGHT (N)		CONTACT FORCE (N)		TANGENTIAL FORCE (N)		RADIAL FORCE (N)		TOTAL FORCE (N)	
			bottom	top	bottom	top	bottom	top	bottom	top	bottom	top	bottom	top
0.800	1	**0.500**	3.957	1.131	9.810	9.810	41.083	0	0.882	8.521	31.313	4.860	31.25	9.810
0.800	1	**0.600**	3.956	1.011	9.810	9.810	35.967	0	0.143	9.495	26.158	2.465	26.158	9.810
0.800	1	**0.700**	3.954	0.733	9.810	9.810	32.024	0	0.206	9.756	22.284	1.031	22.314	9.810

TABLE-2:
CONSTANT MASS & RADIUS, VARYING INITIAL HEIGHT

INITIAL HEIGHT (m)	MASS (kg)	RADIUS (m)	VELOCITY (m/s)		WEIGHT (N)		CONTACT FORCE (N)		TANGENTIAL FORCE (N)		RADIAL FORCE (N)		TOTAL FORCE (N)	
			bottom	top	bottom	top	bottom	top	bottom	top	bottom	top	bottom	top
0.800	1	0.500	3.957	1.131	9.810	9.810	41.083	0	0.882	8.521	31.313	4.860	31.325	9.810
0.900	1	0.500	4.201	1.533	9.810	9.810	45.108	0	0.340	8.109	35.304	5.521	35.306	9.810
1.00	1	0.500	4.426	1.710	9.810	9.810	48.954	0	0.791	6.956	39.176	6.917	39.184	9.810

NOTE:

- The bottom point refers to the lowest point on the loop where the ball starts its circular motion after being released from an initial height.
- The top point refers to the highest point the ball reaches in the loop before starting descending back down.

FOR COMPLETE CIRCULAR MOTION:

Radius:	0.500	m
Initial height:	1.250	m
Gravitational acceleration:	9.81	m/s²
Mass:	1.000	kg

CONCLUSION:

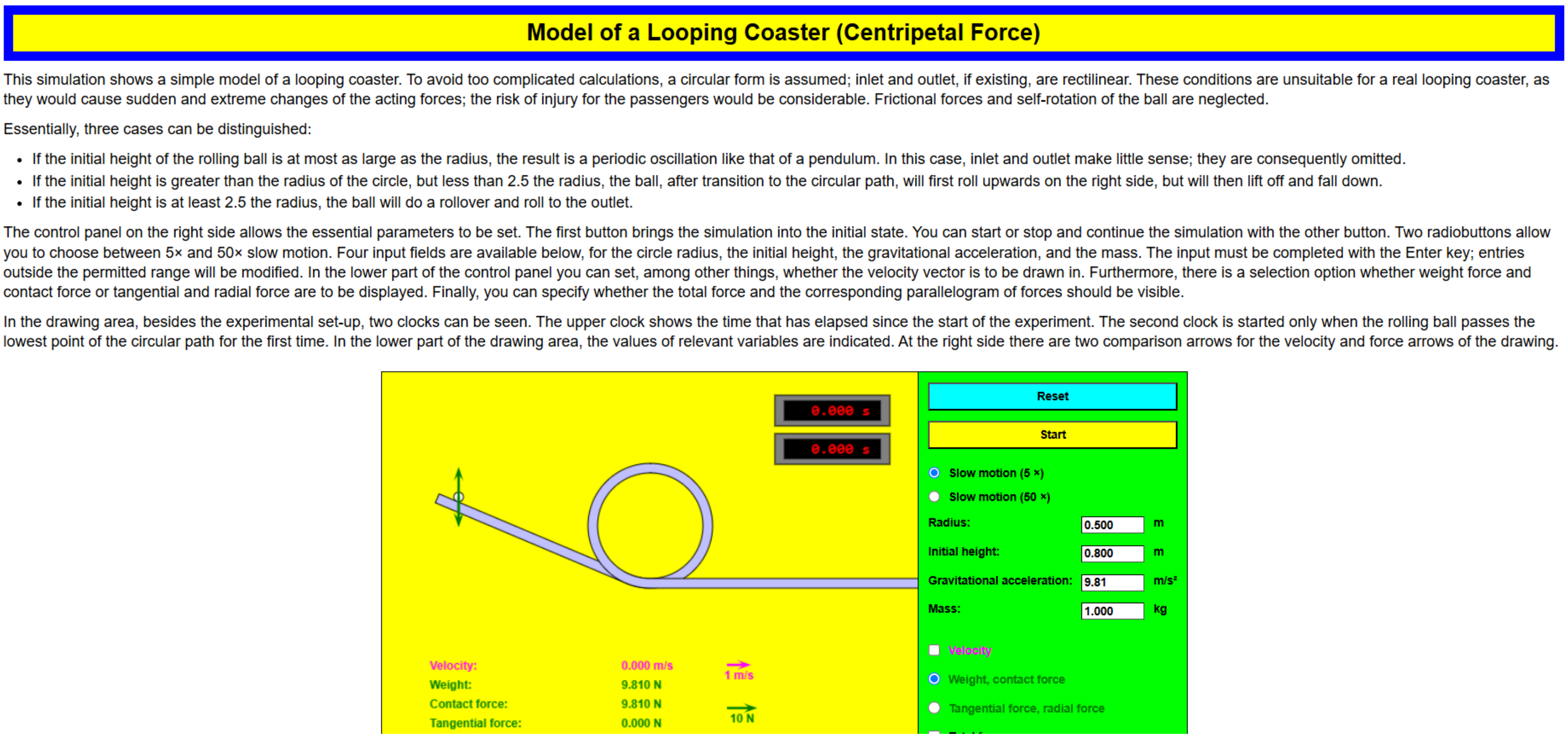
Increasing the radius , reduces the top velocity slightly, decreases the bottom contact force, and has minimal effect on tangential forces and velocity at the bottom.

As the initial height increases, both the velocities and forces at the top and bottom increase, with the contact force at the bottom rising due to higher centripetal force requirements.

For a ball to complete circular motion in a loop, the initial height must be at least **2.5 times** the radius of the loop ($h \geq 2.5R$) to ensure the ball has sufficient velocity at the top of the loop to stay in motion and maintain contact.

References: https://www.walter-fendt.de/html5/phen/

Image 1:Model of a Looping Coaster (Centripetal Force) demonstration.



Model of a Looping Coaster (Centripetal Force)

This simulation shows a simple model of a looping coaster. To avoid too complicated calculations, a circular form is assumed; inlet and outlet, if existing, are rectilinear. These conditions are unsuitable for a real looping coaster, as they would cause sudden and extreme changes of the acting forces; the risk of injury for the passengers would be considerable. Frictional forces and self-rotation of the ball are neglected.

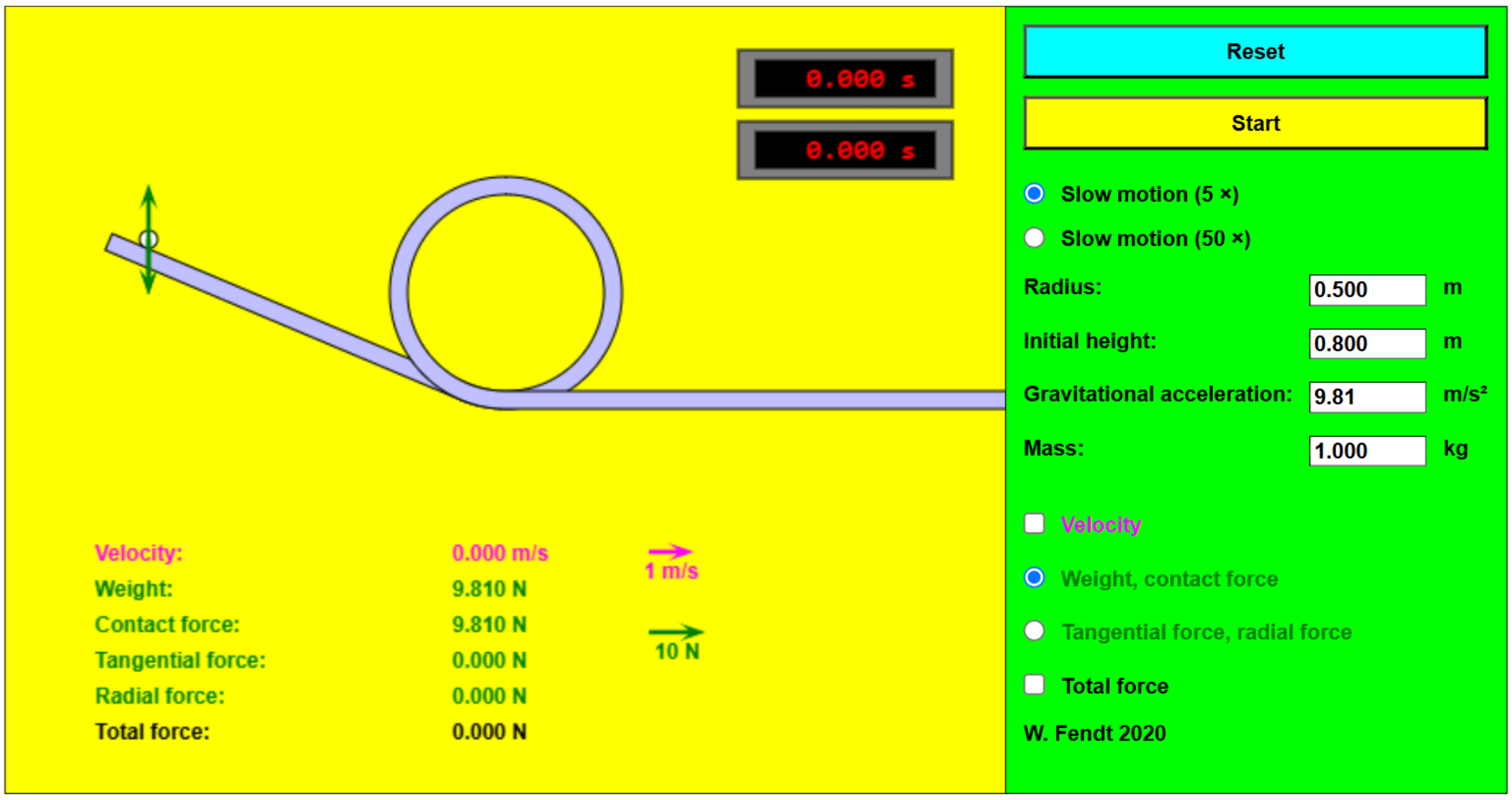
Essentially, three cases can be distinguished:

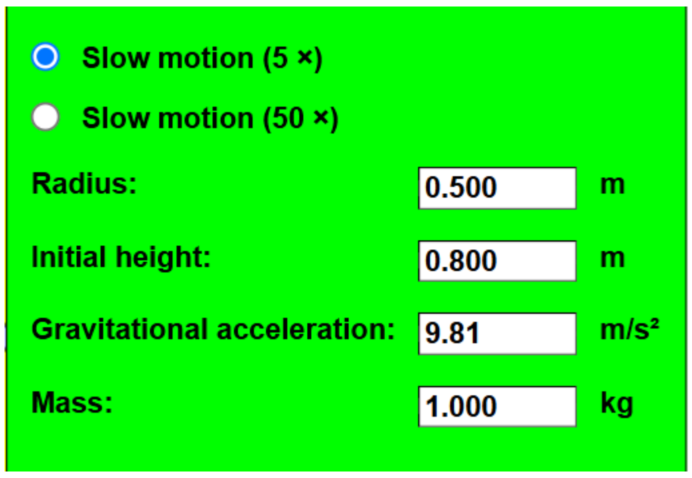
- If the initial height of the rolling ball is at most as large as the radius, the result is a periodic oscillation like that of a pendulum. In this case, inlet and outlet make little sense; they are consequently omitted.
- If the initial height is greater than the radius of the circle, but less than 2.5 the radius, the ball, after transition to the circular path, will first roll upwards on the right side, but will then lift off and fall down.
- If the initial height is at least 2.5 the radius, the ball will do a rollover and roll to the outlet.

The control panel on the right side allows the essential parameters to be set. The first button brings the simulation into the initial state. You can start or stop and continue the simulation with the other button. Two radiobuttons allow you to choose between 5× and 50× slow motion. Four input fields are available below, for the circle radius, the initial height, the gravitational acceleration, and the mass. The input must be completed with the Enter key; entries outside the permitted range will be modified. In the lower part of the control panel you can set, among other things, whether the velocity vector is to be drawn in. Furthermore, there is a selection option whether weight force and contact force or tangential and radial force are to be displayed. Finally, you can specify whether the total force and the corresponding parallelogram of forces should be visible.

In the drawing area, besides the experimental set-up, two clocks can be seen. The upper clock shows the time that has elapsed since the start of the experiment. The second clock is started only when the rolling ball passes the lowest point of the circular path for the first time. In the lower part of the drawing area, the values of relevant variables are indicated. At the right side there are two comparison arrows for the velocity and force arrows of the drawing.

IMAGE 2: Set the initial parameters

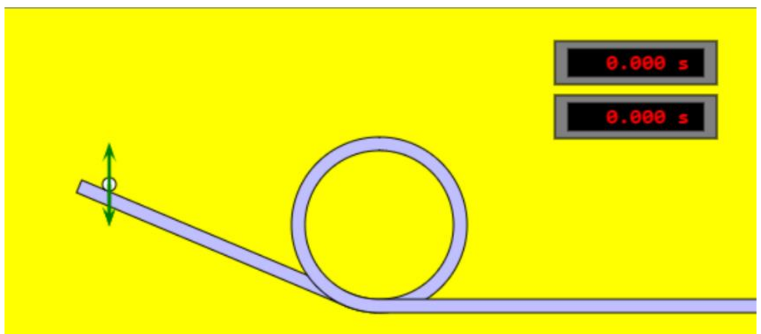




(adjustable parameters & speed can be varied)

IMAGE 3: Resultant parameters

(Result)


(Trajectory)

Clock 1- The upper clock shows the time that has elapsed since the start of the experiment.

Clock 2- The second clock is started only when the rolling ball passes the lowest point of the circular path for the first time.