5.1 The First Law: The Law of Inertia

How does changing an object’s inertia affect its motion?

Newton’s first law states that objects tend to keep doing what they are doing unless acted on by an unbalanced force. This law applies to both objects at rest and objects in motion.

In this investigation, you will:

- change the Energy Car’s inertia to see what affect it has on the Energy Car’s motion.
- apply Newton’s first law to describe the Energy Car’s motion.

1 Making a prediction

Newton’s first law of motion applies to objects at rest and objects in motion. The first law can also be called the law of inertia. To understand why, consider what inertia is. Inertia is a property of matter that resists a change in motion. Inertia comes from an object’s mass. Because of inertia, objects at rest remain at rest, and objects in motion remain in motion, unless acted upon by a net force. You will investigate the first law by launching the Energy Car on a flat track and seeing what happens when you change the car’s inertia.

a. You will launch an Energy Car several times on the flat track, and you will change the number of marbles in the car each time. Write a hypothesis to address the question; “How will changing the inertia of the car affect the car’s motion on the flat track?” Your hypothesis should follow this format: “If inertia affects the car’s motion on the flat track, then when I add more marbles to the car, the car____.”

2 Setting up the experiment

1. Attach a foot to each end of the SmartTrack so it sits level on the table. Check it with the bubble level and adjust the feet as necessary to make the track level.
2. Attach the velocity sensor to the end of the SmartTrack.
3. Fasten a rubber band on the launcher and attach it to the SmartTrack as shown in the picture above.
4. Turn the DataCollector on and then plug the velocity sensor into the DataCollector.
5. At the home window, select data collection mode.
6. At the go window, choose setup at the bottom of the screen.
7. At the setup window, choose standard mode, 200 samples, and 50 Hz. This will allow the DataCollector to collect 50 samples of data from the velocity sensor each second.
8. Practice launching the Energy Car with no marbles. Once you have a consistent launch technique, get the car ready to launch, press the go button on the DataCollector, and launch the car.
9. Switch between meter, table and graph view to study your data.

Materials List

- SmartTrack
- Energy Car
- Steel marbles
- Rubber band
- Track feet (2)
- Bubble level
- Velocity sensor
- DataCollector
Investigation 5.1 The First Law: The Law of Inertia

a. Describe what happens to the Energy Car’s velocity as it moves along the track. Explain why this happens.

b. An object at rest remains at rest unless acted upon by an outside force. What is the outside force that acts on the car to disturb its state of rest at the start of the track?

c. An object in motion remains in motion unless acted upon by an outside force. What outside force acts on the car to change its motion as it moves along the track?

3 Conducting the experiment and reporting back

a. Design an experiment to test the hypothesis you stated in part 1a. What is your procedure?

b. Create a data table and a graph to communicate your results.

c. Summarize your findings. Be sure to refer back to your hypothesis.

4 Reflecting on Newton’s first law

a. State Newton’s first law in your own words.

b. Place the Energy Car in the center of the track so it stays at rest. What do you know about the forces on the Energy Car? Identify the forces acting on it.

c. If the Energy Car is moving, and there are no unbalanced forces acting on it, does its speed increase, decrease, or remain the same? Explain.

d. Were any forces acting on the Energy Car as it rolled along the level track? Identify the forces. Explain how Newton’s first law is applied to describe the motion you observed.

e. What changes occur in the forces acting on the Energy Car when the track is tilted slightly up or down? Explain how the first law is applied to describe the observed motion in the case of an uphill or downhill slope.
5.2 The Second Law: Force, Mass, and Acceleration

What is the relationship between force, mass, and acceleration?

British scientist George Atwood (1746–1807) used two masses on a light string running over a pulley to investigate the effect of gravity. You will build a similar device, aptly called an Atwood’s machine, to explore the relationship between force, mass, and acceleration.

In this investigation, you will:

- measure the acceleration for an Atwood’s machine of fixed total mass.
- create a graph of force versus acceleration for the Atwood’s machine.
- determine the slope and y-intercept of your graph, and relate them to Newton’s second law.

1 Analyzing the Atwood’s machine

To accelerate a mass, you need a net force. Newton’s second law shows the relationship between force, mass, and acceleration:

\[
F = ma
\]

The Atwood’s machine is driven by a net force equal in magnitude to the weight difference between the two mass hangers. You will vary the two masses, \(m_1\) and \(m_2\), but you will keep the total mass constant. As you move plastic washers from \(m_2\) to \(m_1\), you will use a photogate to measure the acceleration of the system. If you know the acceleration and the total mass of the system, you will be able to calculate the net force that is responsible for accelerating the system. The equation for the system’s motion is a variation of the basic second law formula:

\[
F_{\text{net}} = (m_1 + m_2)a
\]

An ideal pulley would be frictionless and massless, and would just redirect the one-dimensional motion of the string and attached masses without interfering with the motion. However, the pulley you will use has mass and there will be some friction involved. For the purpose of this investigation, we will neglect the mass of the pulley, but we will be able to analyze the friction involved with our Atwood’s machine. To represent the friction present in the system, you must subtract it from the net force, since the friction opposes the force of weight provided by \(m_1\) and \(m_2\):

\[
F_{\text{net}} - \text{friction} = (m_1 + m_2)a
\]

It is easiest to move the friction force \(f\) to the other side of the equation, so you get:

\[
F_{\text{net}} = (m_1 + m_2)a + f
\]
Setting up the Atwood’s machine

1. Set up the Atwood’s machine as shown in the photograph at right. Attach the double pulley to the top of the physics stand. You will only use the striped pulley.

2. Attach the mass hangers to the red safety string. Place 10 steel washers on the other mass hanger. This will be \( m_1 \). Place eight steel washers and six plastic washers on one mass hanger. This will be \( m_2 \). Place the string over the dynamic pulley.

3. Pull \( m_2 \) down to the stand base. Place a sponge or some other small cushion on the base to protect it from the falling \( m_1 \). Let go of \( m_2 \) and observe the motion of the Atwood’s machine.

a. Which mass moves downward and why?

b. What would happen if \( m_1 \) and \( m_2 \) were equal masses? Why?

c. Do the masses accelerate when they move? Explain.

d. How does the acceleration of \( m_1 \) compare to the acceleration of \( m_2 \)?

e. The system’s net force equals the weight difference of the mass hangers. Write a simple formula that will allow you to use the mass difference and \( g \), the acceleration due to gravity, to calculate the weight difference of the mass hangers.

Collecting data

1. Find the total mass of \( m_1 \) and \( m_2 \) and record in Table 1.

2. Attach a photogate to the double pulley as shown at right. Plug the photogate into the DataCollector (input A). The striped pattern on the pulley will break the light beam of the photogate as the pulley rotates.

3. Turn on the DataCollector. At the home window, select data collection mode.

4. At the go window, tap on the setup option at the bottom of the screen.

5. In the setup window, choose standard mode.

6. For photogate A (PG\(_A\)), select acceleration in m/s\(^2\). Set the PG\(_B\) option to none.

7. Pull \( m_2 \) to the base. Tap go at the bottom of the setup window.

8. When the experiment has started, release \( m_2 \). When the hanger falls onto the cushion, press the button on the top right of the DataCollector to stop the experiment.

9. Select the table and/or graph option at the bottom of the screen, and study the acceleration data. The acceleration should be constant. Record the acceleration in Table 1. Calculate the net force (see your answer to 2e) and record it in Table 1.

10. Transfer one of the plastic washers from \( m_2 \) to \( m_1 \).

11. Press the button on the DataCollector to resume data collection. Repeat steps 7–10 until you have transferred all of the plastic washers to \( m_1 \).
Table 1: Acceleration and force data

<table>
<thead>
<tr>
<th>Acceleration (m/s²)</th>
<th>Calculated net force (N)</th>
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</thead>
<tbody>
<tr>
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<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

4 Analyzing the data

a. Make a net force vs. acceleration graph (force on the y-axis and acceleration on the x-axis). Draw a best-fit line through the data points.

b. What kind of relationship does the graph show? Is this consistent with Newton’s second law? Explain.

c. Determine the slope of your line. What is the significance of the slope in your experiment?

d. Compare your slope and the known total mass of the system. What is the percent difference? What could account for any difference?

e. Determine the y-intercept of your line. The equation for a line is \( y = mx + b \) (\( m \) is the slope and \( b \) is the y-intercept). Substitute your variables in for \( y, m, \) and \( x \). Compare this equation to the one presented in part 1.

\[ F_{\text{net}} = (m_1 + m_2)a + f \]

f. Based on your answer to the previous question (4e), what does the y-intercept represent? Does this value make sense? Explain.
5.3 Newton’s Third Law: Action and Reaction

What happens when equal and opposite forces act on a pair of Energy Cars?

When you apply a force to throw a ball, you also feel the force of the ball against your hand. That is because all forces come in pairs called action and reaction. Newton’s third law of motion states that there can never be a single force (action) without its opposite (reaction) partner. Action and reaction forces always act in opposite directions on two different objects. You can set up two Energy Cars to study Newton’s third law.

In this investigation, you will:
- link two Energy Cars to create an action/reaction force pair.
- use different numbers of marbles in each car to see how motion is affected.
- relate the cars’ motion to Newton’s third law.

Materials List
- SmartTrack
- Energy Cars (one blue and one orange)
- Energy Car link
- Steel marbles
- Rubber band
- Track feet (2)
- Bubble level
- Velocity sensor
- DataCollector

1 Setting up an action/reaction force pair

1. Adjust the SmartTrack so it sits level on the table. Check it with the bubble level and adjust the feet as necessary to make the track level.
2. Attach the velocity sensor to the end of the SmartTrack.
3. Place one steel marble in each car, and wrap one car with a rubber band.
4. Place the two cars, “nose to notch” in the middle of the track.
5. Squeeze the cars together and attach them with the car link.
6. Position the attached car pair in the middle of the track so the blue car is closest to the velocity sensor. Make sure all four wheels of both cars are on the track.
7. With a very quick upward motion, pull the link straight up and out from the cars. CAUTION: Wear eyeglasses or safety glasses to avoid injury.

a. Describe how the cars move when you remove the car link.

b. How does Newton’s third law of motion explain the motion of the cars when you remove the car link?

c. You will use different numbers of marbles in each car to see how that affects the cars’ motion. Write a hypothesis to address the question “What happens when equal and opposite forces act on objects that have different masses?” Your hypothesis should follow this format: “If equal and opposite forces act on objects of different masses, then ______.”
2 Collecting data

1. Place one steel marble in each car, and wrap one car with a rubber band.
2. Place the two cars, “nose to notch” in the middle of the track.
3. Squeeze the cars together and attach them with the Energy Car link.
4. Position the attached car pair in the middle of the track so the blue car is closest to the velocity sensor. Make sure all four wheels of both cars are on the track.
5. Plug the velocity sensor into input 1 on the DataCollector.
6. Turn the DataCollector on. At the home window, select data collection mode.
7. At the go window, choose setup at the bottom of the screen.
8. At the setup window, choose standard mode, 200 samples, and 0.02 Hz. This will allow the DataCollector to collect 50 samples of data from the velocity sensor each second.
10. With a very quick upward motion, pull the link straight up and out from the cars. CAUTION: Wear eyeglasses or safety glasses to avoid injury.
11. When the cars stop moving, press the button on the DataCollector enclosure to stop the experiment.
12. Switch from meter to table and graph view to study your data. Go to setup to note the name of the experiment in case you want to go back and look at the data later. Record the maximum velocity of the blue car in Table 1. You can only record the blue car’s data, because it was the car the motion detector could “see.”
13. Attach the cars with the energy link again, and position them so the orange car is closest to the velocity sensor. Each car should still have one marble. Set up a new experiment on the DataCollector and repeat steps 9–13.
14. Change the marble configuration as listed in Table 1 and repeat the experiment. Continue until you have completed Table 1. For each trial, you will have to collect two sets of data—one with the blue car facing the velocity sensor, and one with the orange car facing the velocity sensor.

Table 1: Action/reaction pair data

<table>
<thead>
<tr>
<th>Trial</th>
<th>Marble pairings for connected cars</th>
<th>Maximum Velocity (cm/s)</th>
<th>Experiment file name</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Blue</td>
<td>Orange</td>
<td>Blue</td>
</tr>
<tr>
<td>1</td>
<td>1 marble</td>
<td>1 marble</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0 marbles</td>
<td>2 marbles</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>2 marbles</td>
<td>2 marbles</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0 marbles</td>
<td>3 marbles</td>
<td></td>
</tr>
</tbody>
</table>
Investigation 5.3 Newton’s Third Law: Action and Reaction

3 Analyzing the data

a. How does the velocity of each car compare when masses are equal?

b. How does the velocity of each car compare when one car has two or three times the mass of the other car?

c. Explain how your velocity data supports the idea that equal and opposite action and reaction forces acted on the once-linked car pairs.

d. If the action-reaction forces are equal in strength when the cars separate, why does one car move at a different velocity than the other car when the masses are unequal, as in trials 2 and 4?

e. Which of Newton’s laws of motion best explains the answer to the previous question (3d)?

f. Compare and contrast the velocity vs. time graphs for the blue car from trial 1 and trial 3.

g. Compare and contrast the velocity vs. time graphs for the orange car from trial 2 and trial 3.

h. What is one common characteristic from all of the velocity vs. time graphs for each car at every trial? Explain why this characteristic is true about all of the motion scenarios.

4 Why don’t equal and opposite forces cancel each other out?

It is easy to get confused about action-reaction forces. People often ask, “Why don’t they cancel each other out?” The reason is that the action and reaction forces act on different objects. Prove that action-reaction forces never act on the same object by doing the following.

a. Create a sketch showing your calculator sitting on top of your textbook which is sitting on top of your desk which is standing on the tile floor.

b. Identify the forces that serve as the action-reaction forces and draw them in your sketch.

c. Now draw a free body diagram that shows each object by itself (the calculator, the textbook, the table, the tile floor, and Earth) and use arrows to represent the forces acting on each particular object.

d. Look at the forces on any one object. Does that one object have both forces from any single action-reaction pair acting on it? Is this true for all of the objects? (This is the key to Newton’s third law: The action-reaction forces are equal in size and opposite in direction but since they act on different objects, they do not cancel each other out.)