PRINCIPLES OF ROCKET FLIGHT

LEARNING OBJECTIVE: Principles of flight for rockets.

DISCUSSION:

Rocket Principles A rocket in its simplest form is a chamber enclosing a gas under pressure. A small opening at one end of the chamber allows the gas to escape, and in doing so provides a thrust that propels the rocket in the opposite direction. A good example of this is a balloon. Air inside a balloon is compressed by the balloon's rubber walls. The air pushes back so that the inward and outward pressing forces balance. When the nozzle is released, air escapes through it and the balloon is propelled in the opposite direction.

When we think of rockets, we rarely think of balloons. Instead, our attention is drawn to the giant vehicles that carry satellites into orbit and spacecraft to the Moon and planets. Nevertheless, there is a strong similarity between the two. The only significant difference is the way the pressurized gas is produced. With space rockets, the gas is produced by burning propellants that can be solid or liquid in form or a combination of the two.

One of the interesting facts about the historical development of rockets is that while rockets and rocket-powered devices have been in use for more than two thousand years, it has been only in the last three hundred years that rocket experimenters have had a scientific basis for understanding how they work.

The science of rocketry began with the publishing of a book in 1687 by the great English scientist Sir Isaac Newton. His book, entitled Philosophiae Naturalis Principia Mathematica, described physical principles in nature. Today, Newton's work is usually just called the Principia. In the Principia, Newton stated three important scientific principles that govern the motion of all objects, whether on Earth or in space.

Knowing these principles, now called Newton's Laws of Motion, rocketeers have been able to construct the modern giant rockets of the 20th century such as the Saturn 5 and the Space Shuttle. Here now, in simple form, are Newton's Laws of Motion.

1. Objects at rest will stay at rest and objects in motion will stay in motion in a straight line unless acted upon by an unbalanced force.

2. Force is equal to mass times acceleration.

3. For every action there is always an opposite and equal reaction.

As will be explained shortly, all three laws are really simple statements of how things move. But with them, precise determinations of rocket performance can be made.

(SHOW NASA FILM ON NEWTON'S LAWS HERE)

Newton's First Law
This law of motion is just an obvious statement of fact, but to know what it means, it is necessary to understand the terms **rest**, **motion**, and **unbalanced force**. Rest and motion can be thought of as being opposite to each other. Rest is the state of an object when it is not changing position in relation to its surroundings. If you are sitting still in a chair, you can be said to be at rest. This term, however, is relative. Your chair may actually be one of many seats on a speeding airplane. The important thing to remember here is that you are not moving in relation to your immediate surroundings. If rest were defined as a total absence of motion, it would not exist in nature. Even if you were sitting in your chair at home, you would still be moving, because your chair is actually sitting on the surface of a spinning planet that is orbiting a star. The star is moving through a rotating galaxy that is, itself, moving through the universe. While sitting "still," you are, in fact, traveling at a speed of hundreds of kilometers per second.

Motion is also a relative term. All matter in the universe is moving all the time, but in the first law, motion here means changing position in relation to surroundings. A ball is at rest if it is sitting on the ground. The ball is in motion if it is rolling. A rolling ball changes its position in relation to its surroundings. When you are sitting on a chair in an airplane, you are at rest, but if you get up and walk down the aisle, you are in motion. A rocket blasting off the launch pad changes from a state of rest to a state of motion. The third term important to understanding this law is **unbalanced force**. If you hold a ball in your hand and keep it still, the ball is at rest. All the time the ball is held there though it is being acted upon by forces. The force of gravity is trying to pull the ball downward, while at the same time your hand is pushing against the ball to hold it up. The forces acting on the ball are balanced. Let the ball go, or move your hand upward, and the forces become unbalanced. The ball then changes from a state of rest to a state of motion.

(Demonstrate with a ball)

In rocket flight, forces become balanced and unbalanced all the time. A rocket on the launch pad is balanced. The surface of the pad pushes the rocket up while gravity tries to pull it down. As the engines are ignited, the thrust from the rocket unbalances the forces, and the rocket travels upward. Later, when the rocket runs out of fuel, it slows down, stops at the highest point of its flight, and then falls back to Earth. Objects in space also react to forces. A spacecraft moving through the solar system is in constant motion. The spacecraft will travel in a straight line if the forces on it are in balance. This happens only when the spacecraft is very far from any large gravity source such as Earth or the other planets and their moons.

If the spacecraft comes near a large body in space, the gravity of that body will unbalance the forces and curve the path of the spacecraft. This happens, in particular, when a satellite is sent by a rocket on a path that is tangent to the planned orbit about a planet. The unbalanced gravitational force causes the satellite's path to change to an arc. The arc is a combination of the satellite's fall inward toward the planet's center and its forward motion. When these two motions are just right, the shape of the satellite's path matches the shape of the body it is traveling around. Consequently, an orbit is produced.

Since the gravitational force changes with height above a planet, each altitude has its own unique velocity that results in a circular orbit. Obviously, controlling velocity is extremely important for maintaining the circular orbit of the spacecraft. Unless another unbalanced force, such as friction with gas molecules in orbit or the firing of a rocket engine in the opposite direction, slows down the spacecraft, it will orbit the planet forever.

Newton’s Third Law

For the time being, we will skip the Second Law and go directly to the Third. *This law states that every action has an equal and opposite reaction*. If you have ever stepped off a small boat that has not been properly tied to a pier, you will know exactly what this law means.

A rocket lifts off from a launch pad only when it expels gas out of its engine. The rocket pushes on the gas, and the gas in turn pushes on the rocket. The whole process is very similar to riding a skateboard. Imagine that a skateboard and rider are in a state of rest (not moving). The rider jumps off the skateboard. In the Third Law, the jumping is called an action. The skateboard responds to that action by traveling some distance in the opposite direction. The skateboard’s opposite motion is called a reaction. When the distance traveled by the rider and the skateboard are compared, it would appear that the skateboard has had a much greater reaction than the action of the rider. This is not the case. The reason the skateboard has traveled farther is that it has less mass than the rider. This concept will be better explained in a discussion of the Second Law.

(Can demonstrate with a skateboard)

With rockets, the action is the expelling of gas out of the engine. The reaction is the movement of the rocket in the opposite direction. To enable a rocket to lift off from the launch pad, the action, or thrust, from the engine must be greater than the weight of the rocket. While on the pad the weight of the rocket is balanced by the force of the ground pushing against it. Small amounts of thrust result in less force required by the ground to keep the rocket balanced. Only when the thrust is greater than the weight of the rocket does the force become unbalanced and the rocket lifts off. In space where unbalanced force is used to maintain the orbit, even tiny thrusts will cause a change in the unbalanced force and result in the rocket changing speed or direction.

One of the most commonly asked questions about rockets is how they can work in space where there is no air for them to push against. The answer to this question comes from the Third Law. Imagine the skateboard again. On the ground, the only part air plays in the motions of the rider and the skateboard is to slow them down. Moving through the air causes friction, or as scientists call it, drag. The surrounding air impedes the action-reaction.

As a result rockets actually work better in space than they do in air. As the exhaust gas leaves the rocket engine it must push away the surrounding air; this uses up some of the energy of the rocket. In space, the exhaust gases can escape freely.

Newton’s Second Law

This law of motion is essentially a statement of a mathematical equation. The three parts of the equation are mass (m), acceleration (a), and force (f). Using letters to symbolize each part, the equation can be written as follows:
$f = ma$

The equation reads: force equals mass times acceleration. To explain this law, we will use an old style cannon as an example. When the cannon is fired, an explosion propels a cannon ball out the open end of the barrel. It flies a kilometer or two to its target. At the same time the cannon itself is pushed backward a meter or two. This is action and reaction at work (Third Law). The force acting on the cannon and the ball is the same.

What happens to the cannon and the ball is determined by the Second Law. Look at the two equations below.

$f = m(cannon)a(cannon)$
$f = m(ball)a(ball)$

The first equation refers to the cannon and the second to the cannon ball. In the first equation, the mass is the cannon itself and the acceleration is the movement of the cannon. In the second equation the mass is the cannon ball and the acceleration is its movement. Because the force (exploding gun powder) is the same for the two equations, the equations can be combined and rewritten below.

$m(cannon)a(cannon) = m(ball)a(ball)$

In order to keep the two sides of the equations equal, the accelerations vary with mass. In other words, the cannon has a large mass and a small acceleration. The cannon ball has a small mass and a large acceleration.

Apply this principle to a rocket. Replace the mass of the cannon ball with the mass of the gases being ejected out of the rocket engine. Replace the mass of the cannon with the mass of the rocket moving in the other direction. Force is the pressure created by the controlled explosion taking place inside the rocket's engines. That pressure accelerates the gas one way and the rocket the other.

Some interesting things happen with rockets that do not happen with the cannon and ball in this example. With the cannon and cannon ball, the thrust lasts for just a moment. The thrust for the rocket continues as long as its engines are firing. Furthermore, the mass of the rocket changes during flight. Its mass is the sum of all its parts. Rocket parts include: engines, propellant tanks, payload, control system, and propellants. By far, the largest part of the rocket's mass is its propellants. But that amount constantly changes as the engines fire. That means that the rocket's mass gets smaller during flight. In order for the left side of our equation to remain in balance with the right side, acceleration of the rocket has to increase as its mass decreases. That is why a rocket starts off moving slowly and goes faster and faster as it climbs into space.

Newton's Second Law of Motion is especially useful when designing efficient rockets. To enable a rocket to climb into low Earth orbit, it is necessary to achieve a speed, in excess of 28,000 km per hour. A speed of over 40,250 km per hour, called escape velocity, enables a rocket to leave Earth and travel out into deep space. Attaining space flight speeds requires the rocket engine to achieve the greatest action force possible in the shortest time. In other words, the engine must burn a large mass of fuel and push the resulting gas out of the engine as rapidly as possible.

Putting Newton’s Laws of Motion Together

An unbalanced force must be exerted for a rocket to lift off from a launch pad or for a craft in space to change speed or direction (**First Law**). The amount of thrust (force) produced by a rocket engine will be determined by the rate at which the mass of the rocket fuel burns and the speed of the gas escaping the rocket (**Second Law**). The reaction, or motion, of the rocket is equal to and in the opposite direction of the action, or thrust, from the engine (**Third Law**).

Activities (do only one of these activities)

Two Activities: Pop Can Hero Engine and Newton Car. All help the Mission Team members gain awareness of Newton’s Laws of Motion.

Activity 1

POP CAN HERO ENGINE

- To demonstrate Newton's Third Law of Motion by using the force of falling water to cause a soda pop can to spin.
- To experiment with different ways of increasing the spin of the can.

Background Information:

Hero of Alexandria invented the Hero engine in the first century B.C. His engine operated because of the propulsive force generated by escaping steam. A boiler produced steam that escaped to the outside through L-shaped tubes bent pinwheel fashion. The steam's escape produced an action-reaction force that caused the sphere to spin in the opposite direction. Hero's engine is an excellent demonstration of Newton's Third Law of Motion (See page 5 for more information about Hero's Engine and pages 15-16 for details about Newton's Third Law of Motion.). This activity substitutes the action force produced by falling water for the steam in Hero's Engine.

Management:

This activity works well with small groups of two or three Mission Team members. Allow approximately 40 to 45 minutes to complete. The activity is divided into two parts.

In Part one the learners construct the engine and test it. Part two focuses on variables that affect the action of the engine. The experiment stresses prediction, data collection, and analysis of results. Be sure to recycle the soda pop cans at the end of the activity.
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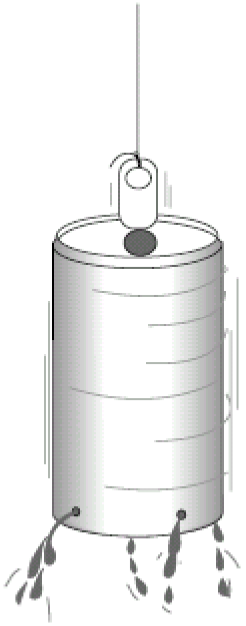


Part One

Materials and Tools:

- Empty soda pop can with the opener lever still attached - one per group of Mission Team members
- Common nail - one per group of Mission Team members
- Nylon fishing line (light weight)
- Bucket or tub of water - several for entire class
- Paper towels for cleanup
- Meter stick
- Scissors to cut fishing line

Description:

A soft drink can suspended by a string spins by the force created when water streams out of slanted holes near the can's bottom.

Part One:

Making a Soda Pop Can Hero Engine:

1. Distribute Mission Team member pages and one soda pop can and one medium-size common nail to each group. Tell the Mission Team members that you will demonstrate the procedure for making the Hero engine.
2. Lay the can on its side and use the nail to punch a single hole near its bottom. Before removing the nail, push the nail to one side to bend the metal, making the hole slant in that direction.
3. Remove the nail and rotate the can approximately 90 degrees. Make a second hole like the first one. Repeat this procedure two more times to produce four equally spaced holes around the bottom of the can. All four holes should slant in the same direction going around the can.
4. Bend the can's opener lever straight up and tie a 40-50 centimeter length of fishing line to it. The soda pop can Hero engine is complete.

Running the Engine:

1. Dip the can in the water tub until it fills with water. Ask the Mission Team members to predict what will happen when you pull the can out by the fishing line.
2. Have each group try out their Hero engine.

Discussion:

1. Why did the cans begin spinning when water poured out of the holes?
2. What was the action? What was the reaction?
3. Did all cans spin equally well? Why or why not?

Part Two:
Experimenting with Soda Pop Can Hero Engines

1. Tell the Mission Team members they are going to do an experiment to find out if there is any relationship between the size of the holes punched in the Hero Engine and how many times it rotates. Ask Mission Team members to predict what they think might happen to the rotation of the Hero engine if they punched larger or smaller holes in the cans. Discuss possible hypotheses for the experiment.

Part Two
Materials and Tools:

- Mission Team member Work Sheets
- Hero Engines from part one
- Empty soda pop can with the opener lever still attached (three per group of Mission Team members)
- Common nails - Two different diameter shafts (one each per group)
- Nylon fishing line (light weight)
- Bucket or tub of water - Several for entire class
- Paper towels for cleanup
- Meter stick
- Large round colored gum labels or marker pens
- Scissors to cut fishing line

How To Bend The Holes

1. Punch hole with nail.
2. With nail still inserted, push upper end of nail to the side to bend the hole.

2. Provide each group with the materials listed for Part Two. The nails should have different diameter shafts from the one used to make the first engine. Identify these nails as small (S) and large (L). Older Mission Team members can measure the diameters of the holes in millimeters. Since there will be individual variations, record the average hole diameter. Have the groups make two additional engines exactly like the first, except that the holes will be different sizes.
3. Discuss how to count the times the engines rotate. To aid in counting the number of rotations, stick a brightly colored round gum label or some other marker on the can. Tell them to practice counting the rotations of the cans several times to become consistent in their measurements before running the actual experiment.
4. Have the Mission Team members write their answers for each of three tests they will conduct on the can diagrams on the Mission Team member Pages. (Test One employs the can created in Part One.) Mission Team members should not predict results for the second and third cans until they have finished the previous tests.
5. Discuss the results of each group's experiment. Did the results confirm the experiment hypothesis?
6. Ask the Mission Team members to propose other ways of changing the can's rotation (Make holes at different distances above the bottom of the can, slant holes in different directions or not slanted at all, etc.) Be sure they compare the fourth Hero Engine they make with the engine previously made that has the same size holes.

Discussion:

1. Compare the way rockets in space change the directions they are facing in space with the way Hero Engines work.
2. How can you get a Hero Engine to turn in the opposite direction?
3. Can you think of any way to put Hero Engines to practical use?
4. In what ways are Hero Engines similar to rockets? In what ways are they different?

Test Number 1
Design a new Hero Engine experiment. Remember, change only one variable in your experiment.
What is your experiment hypothesis?
Compare this engine with the engine from your first experiment that has the same size holes.
Based on your results, was your hypothesis correct? Why?

Test Number 2
Based on your results, was your hypothesis correct? Why?
Mark each can to help you count the spins.
Test each Hero Engine and record your data on the cans below.

Test Number 3
Design an experiment that will test the effect that the size of the holes has on the number of spins the can makes. What is your experiment hypothesis?
Describe what you learned about Newton's Laws of Motion by building and testing your Hero Engines.

Share your findings.

Activity II

Newton Car

Management:

Conduct this activity in groups of three Mission Team members. Use a smooth testing surface such as a long, level table top or uncarpeted floor. The experiment has many variables that Mission Team members must control including: the size of the string loop they tie, the placement of the mass on the car, and the placement of the dowels. Discuss the importance of controlling the variables in the experiment with your Mission Team members.

Making the Newton Car involves cutting blocks of wood and driving three screws into each block. Refer to the diagram on this page for the placement of the screws as well as how the Newton Car is set up for the experiment. Place the dowels in a row like railroad ties and extend them to one side as shown in the picture. If you have access to a drill press, you can substitute short dowels for the screws. It is important to drill the holes for the dowels perpendicular into the block with the drill press. Add a drop of glue to each hole. The activity requires Mission Team members to load their "slingshot" by stretching the rubber bands back to the third screw and holding it in place with the string. The simplest way of doing this is to tie the loop first and slide the rubber bands through the loop before placing the rubber bands over the two screws. Loop the string over the third screw after stretching the rubber bands back. Use a match or lighter to burn the string. The small ends of string left over from the knot acts as a fuse that permits the Mission Team members to remove the match before the string burns through.

Teachers may want to give Mission Team member groups only a few matches at a time. To completely conduct this experiment, Mission Team member groups will need six matches. It may be necessary for a practice run before starting the experiment. As an alternative to the matches, Mission Team members can use blunt nose scissors to cut the string. This requires some fast movement on the part of the Mission Team member doing the cutting. The Mission Team member needs to move the scissors quickly out of the way after cutting the string. Tell the Mission Team members to tie all the string loops they need before beginning the experiment. The loops should be as close to the same size as possible. Refer to the diagram on the Mission Team member pages for the actual size of the loops. Loops of different sizes will introduce a significant variable into the experiment, causing the rubber bands to be stretched different amounts. This will lead to different accelerations with the mass each time the experiment is conducted. Use plastic 35 millimeter film canisters for the mass in the experiments. Direct Mission Team members to completely fill the canister with various materials, such as seeds, small nails, metal washers, sand, etc. This will enable them to vary the mass twice during the experiment.

Have Mission Team members weigh the canister after it is filled and record the mass on the Mission Team member sheet. After using the canister three times, first with one rubber band and then two and three rubber bands, Mission Team members should refill the canister with new material for the next three tests.

Refer to the sample graph for recording data. The bottom of the graph is the distance the car travels in each test. Mission Team members should plot a dot on the graph for the distance the car traveled. The dot should fall on the y-axis line representing the number of rubber bands used and on the x-axis for the distance the car traveled. After plotting three tests with a particular mass, connect the dots with lines. The Mission Team members should use a solid line for Mass 1 and a line with large dashes for Mass 2. If the Mission Team members have carefully controlled their variables, they should observe that the car traveled the greatest distance using the greatest mass and three rubber bands. This conclusion will help them conceptualize Newton's Second Law of Motion.

Background Information:

The Newton car provides an excellent tool for investigating Isaac Newton’s Second Law of Motion. The law states that force equals mass times acceleration. In rockets, the force is the action produced by gas expelled from the engines. According to the law, the greater the gas that is expelled and the faster it accelerates out of the engine, the greater the force or thrust. More details on this law can be found on page 16 of this guide. The Newton Car is a kind of a slingshot. A wooden block with three screws driven into it forms the slingshot frame. Rubber bands stretch from two of the screws and hold to the third by a string loop. A mass sits between the rubber bands. When the string is cut, the rubber bands throw the block to produce an action force. The reaction force propels the block in the opposite direction over some dowels that act as rollers (Newton's Third Law of Motion).

This experiment directs Mission Team members to launch the car while varying the number of rubber bands and the quantity of mass thrown off. They will measure how far the car travels in the opposite direction and plot the data on a graph. Repeated runs of the experiment should show that the distance the car travels depends on the number of rubber bands used and the quantity of the mass being expelled. Comparing the graph lines will lead Mission Team members to Newton's Second Law of Motion.

Discussion:

1. How is the Newton Car similar to rockets?
2. How do rocket engines increase their thrust?
3. Why is it important to control variables in an experiment?

Assessment:

Conduct a Mission Team discussion where Galaxy Explorers share their findings about Newton's Laws of Motion. Ask them to compare their results with those from previous activities such as Pop Can Hero Engine. Collect and review completed Mission Team member pages.

Extensions:

Obtain a toy water rocket from a toy store. Try launching the rocket with only air and then with water and air and observe how far the rocket travels.

Objective:

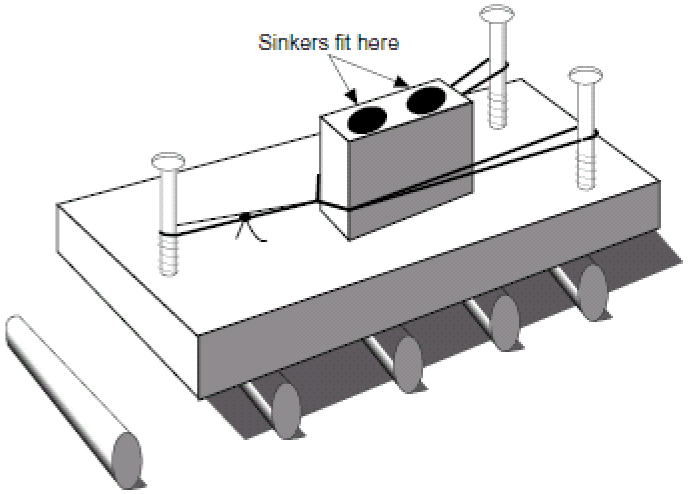
To investigate how increasing the mass of an object thrown from a Newton Car affects the car's acceleration over a rolling track (Newton's Second Law of Motion).

Description:

In this activity, Mission Team members test a slingshot-like device that throws a mass causing the car to move in the opposite direction.

Materials and Tools:

- 1 Wooden block about 10 x 20 x 2.5 cm
- 3 3-inch No. 10 wood screws (round head)
- 12 Round pencils or short lengths of similar dowel
- Plastic film canister
- Assorted materials for filling canister (e.g. washers, nuts, etc.)
- 3 Rubber bands
- Cotton string
- Safety lighter
- Eye protection for each Mission Team member
- Metric beam balance (Primer Balance)
- Vice
- Screwdriver
- Meter stick



1. Tie 6 string loops this size.
2. Fill up your film canister and weigh it in grams. Record the mass in the Newton Car Report chart.
3. Set up your Newton Car as shown in the picture. Slip the rubber band through the string loop. Stretch the rubber band over the two screws and pull the string back over the third screw. Place the rods 6 centimeters apart. Use only one rubber band the first time.
4. Put on your eye protection!
5. Light the string and stand back. Record the distance the car traveled on the chart.
6. Reset the car and rods. Make sure the rods are 6 centimeters apart! Use two rubber bands. Record the distance the car travels.
7. Reset the car with three rubber bands. Record the distance it travels.
8. Refill the canister and record its new mass.
9. Test the car with the new canister and with 1, 2, and 3 rubber bands. Record the distances the car moves each time.
10. Plot your results on the graph. Use one line for the first set of measurements and a different line for the second set.

Newton Car Report

Describe what happened when you tested the car with 1, 2, and 3 rubber bands.

Write a short statement explaining the relationship between the amount of mass in the canister, the number of rubber bands, and the distance the car traveled.