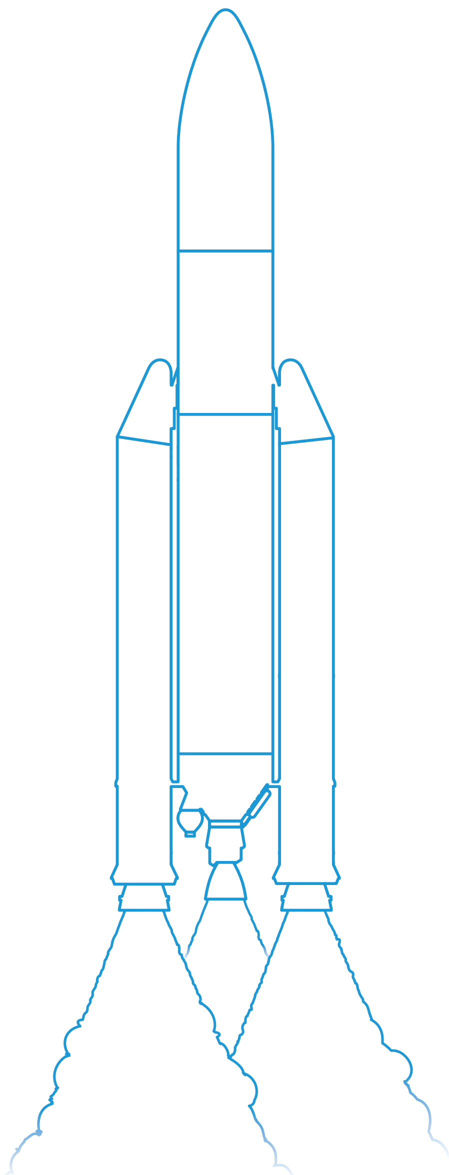
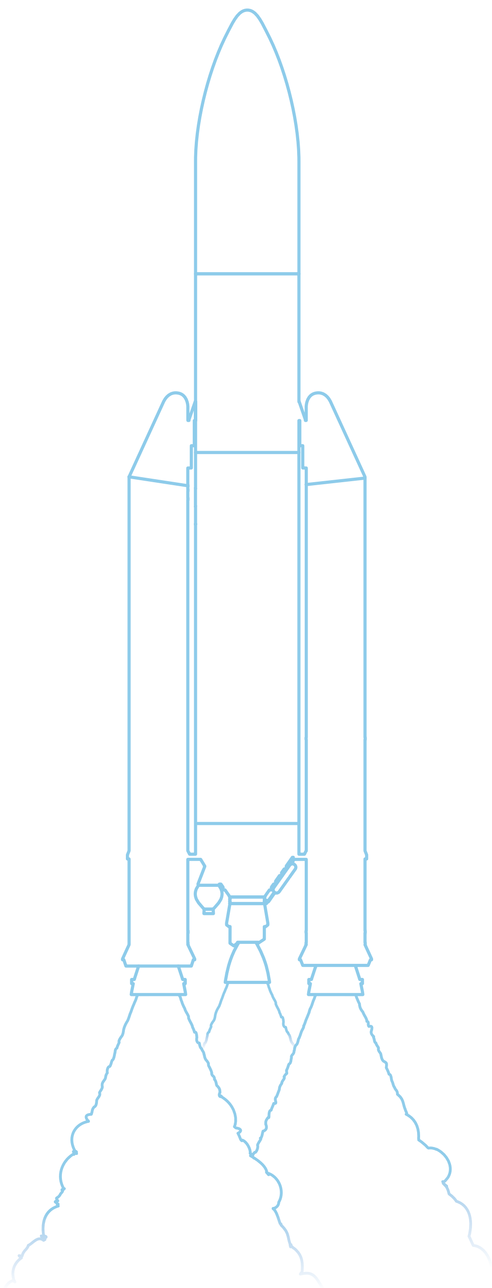
teach with space

→ WHOOSH BOTTLE

Applying Newton's laws to rockets





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→ WHOOSH BOTTLE

Applying Newton's laws to rockets

FAST FACTS

Age range: 14-17 years old

Type: Practical demonstration or student activity

Complexity: Easy

Teacher preparation time required: 20 minutes to read through activity

Lesson time required: 45 minutes

Location: Laboratory

Includes use of: Highly flammable fuels (ethanol or other alcohol)

Outline

In this activity, alcohol and air are mixed in a large plastic water bottle before being ignited, to simulate the physics principles of chemical rocket engines. The activity can either be run as a teacher demonstration or a student activity, for which there are separate protocols. The students will observe a rapid reaction accompanied by a dramatic "whoosh" sound and flames. They will discuss the similarities and differences between the laboratory reaction and the reaction that occurs in rocket engines. Students will finish the activity by mathematically applying Newton's laws of motion to what they have seen.

Students will learn

- How chemical rocket engines work
- How to apply Newton's three laws of motion to rocket engines
- The relationship between thrust and acceleration
- Calculations related to forces

Students will improve

- Their ability to apply knowledge gained through experimental observations to solve theoretical problems
- Their ability to work safely in a laboratory

You will also need

↑ Whoosh bottle – Classroom Demonstration Video. See links section.

Curriculum links

- Physics – rocket launches, action/reaction forces, Newton's laws
- Chemistry – combustion reactions

→ ACTIVITY 1: BURN FUEL, BURN!

In this activity, a mixture of air and alcohol is ignited inside a plastic bottle, simulating what happens during the ignition of fuels in a rocket launch. Students will see a rapid reaction, accompanied by a dramatic "whoosh" sound and flames, demonstrating the large amount of energy released in combustion reactions. Chemical rocket engines use the high pressures and temperatures of combustion to accelerate the exhaust gases and to push the rocket upwards.

Experiment preparation

The Whoosh bottle Classroom Demonstration Video, available on ESA's Education website, shows the complete set-up of this activity, and describes how to carry it out. The protocol presented in this teacher guide provides information on the equipment and instructions for you to do the activity as a teacher demonstration (Figure 1). For students to do this activity as a laboratorial activity they should use small plastic bottles as suggested in the protocol in the students' activity sheet.

This demonstration is best performed in a dark room.

Equipment

- 1 or more large plastic water bottles as used in water coolers (approximately 20 litres)
- 15 ml of industrial methylated spirit (cheaper) or pure ethanol (more expensive)
- Match and splint
- Metre ruler (the splint should be taped to the ruler to maintain a safe distance when lighting the large bottle)
- Safety glasses
- 1 pair of heavy duty gloves

Health & safety

- Ethanol (and other alcohol if used) is highly flammable. Do not use near naked flames.
- Ensure that flammable chemicals, including all alcohols, are kept in stoppered containers when not in use.
- Safety glasses must be worn at all times.
- Verify that the bottles are not damaged. If any cracks are present, use a different bottle.
- Always wear gloves when lighting the bottle. Do not hold your body over the top of the bottle.
- Warn all students and observers about the possible noise levels and ask those with sensitive hearing to cover their ears.
- Do not conduct the demonstration upside down in an attempt to launch the whoosh bottle.
- Follow the general safety control measures in the laboratory.

Exercise

1. Put on safety glasses.

2. Remove the lid from the water bottle and ensure the bottle is completely dry.

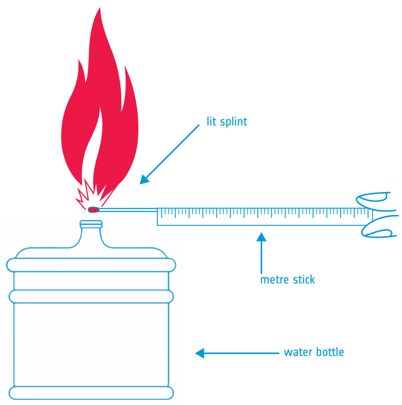
3. Pour about 15 ml of fuel into the bottle. Suitable fuels include methylated spirits, methanol, ethanol, propan-1-ol and propan-2-ol.

4. Replace the lid and shake well for at least one minute. The shaking will help to vaporise the alcohol.

5. If any fuel is left at the bottom of the bottle, pour it out and replace the lid. Make sure that students see this being done.

Figure 1

lighting the whoosh bottle



↑ Whoosh bottle set-up (for teacher demonstration)

6. Attach a splint to the end of a metre ruler and hold it at a slight downward angle. Light the splint, remove the seal of the bottle, and hold the end of the ruler so that the burning splint is over the neck of the bottle (Figure 1).

7. The reaction happens fast and is loud! Once the reaction is complete, tip the bottle upside down to show students the drops of colourless liquid that fall out. The bottle can be passed around amongst the students for them to feel how warm it is – particularly on the top surface.

8. If more bottles are available, it can be interesting to repeat the experiment with other fuels. Alternatively the same bottle can be reused after recycling the air using a vacuum pump run in reverse, or after pumping fresh air in to the bottle using a bicycle pump.

Answers to discussion questions

1. Explain why the bottle should be shaken after adding the alcohol.
   To help vaporise the alcohol.

2. The reaction was accompanied by a whoosh sound. Explain where this sound came from.
   The whoosh sound is a result of the exhaust gases being forced rapidly out of the narrow opening of the bottle. This is a consequence of the expansion of hot gas inside the bottle.

3. Considering Newton's third law, identify the forces that act on the bottle during the combustion reaction.
   The three forces are:
   - The weight of the bottle
   - The normal force (from the ground)
   - The thrust produced by the exhaust gases (carbon dioxide and water vapour). These gases are expelled upward out of the bottle, thus Newton's third law tells us that the equal and opposite reaction force on the bottle is directed downwards into the floor.

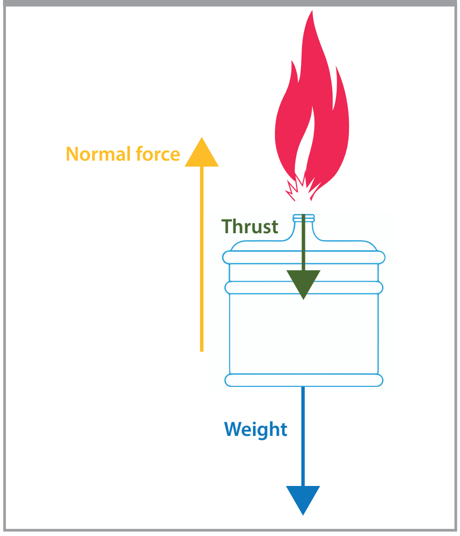
4. Draw a force diagram showing the forces acting on the bottle during the combustion reaction.

Note that the arrow for the normal force should be approximately equal to the combined size of the weight and thrust arrows (Figure 2).

5. Draw a force diagram showing the forces acting on a rocket at the moment of launch, immediately after it has left the ground. Ignore air resistance.

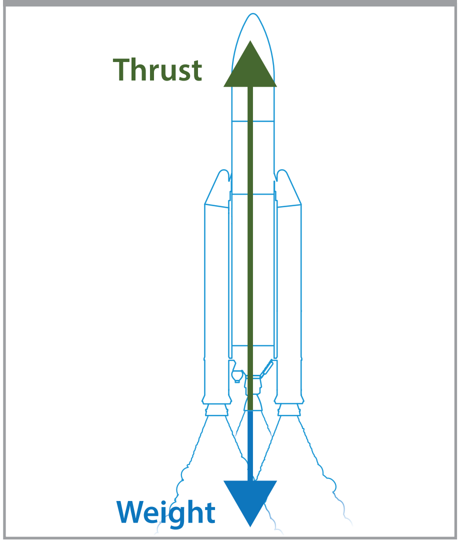
Note that the arrow for the thrust should be bigger than the arrow for the weight (Figure 3).

Figure 2



↑ Forces acting on the whoosh bottle during the combustion reaction

Figure 3



↑ Forces acting on a rocket during launch

6. Describe the similarities and differences between the two diagrams you have drawn.

The forces that are similar are the weight and the thrust. However, on the bottle the thrust generated by the exhaust gases is directed downwards into the floor, whereas in the rocket the thrust is directed upwards.

7. Explain the effects of the forces in the two examples (the whoosh bottle and the rocket).

The whoosh bottle is effectively an inverted version of a rocket launch. In this case, the exhaust gases produce a downward force (thrust) due to Newton's third law. Because the bottle is placed on the ground or on a table, this thrust is actually acting on the entire mass of the Earth meaning that it does not have any effect.

In the case of a rocket, the thrust is directed upwards and acts only on the mass of the rocket, therefore accelerating it at a relatively high rate (Newton's first and second laws). As the rocket accelerates through the lower atmosphere, there will be considerable aerodynamic drag, especially in the first two or three minutes after launch when velocities are high and the atmosphere is still relatively dense. Above altitudes of 120 km, the atmospheric drag becomes minimal. Although gravitational forces diminish with distance, they never completely disappear.

→ ACTIVITY 2: APPLYING NEWTON'S SECOND LAW TO ROCKETS

To launch a rocket into space there needs to be enough thrust to counteract gravity. In this activity, students apply Newton's second law to rockets to calculate the amount of fuel a rocket needs to create the necessary thrust to launch.

Answers to exercise

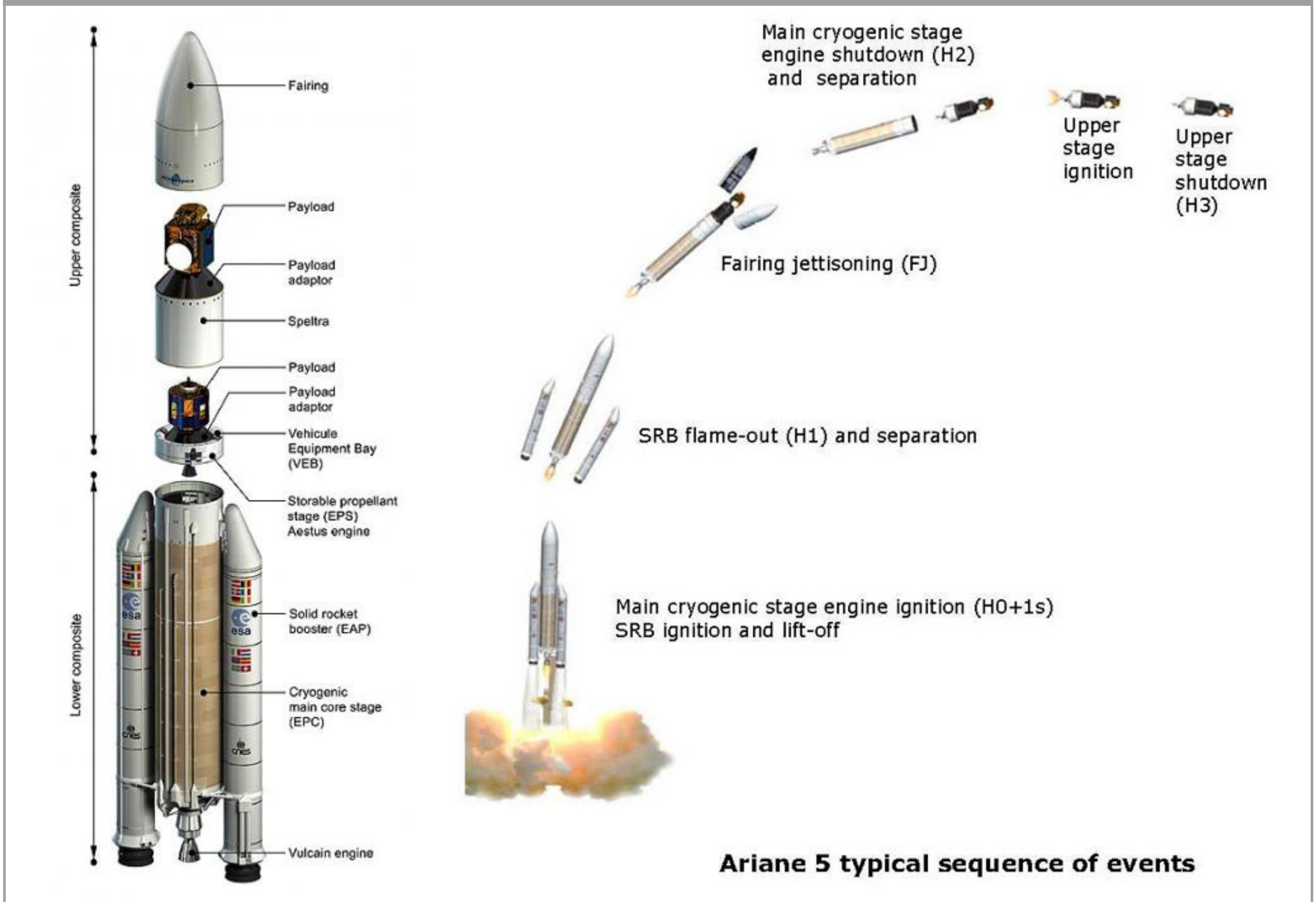
1. An Ariane 5 ECA rocket is on the launch pad in Kourou, French Guiana. The lower section of Ariane 5 ECA consists of the main cryogenic core stage (EPC) and the two solid propellant boosters (EAP) (see Figure 4). The thrust generated from its engines is 960 kN from the main EPC cryogenic stage and 6450 kN from each of the two solid propellant boosters attached to it. The total mass of the rocket on the Launchpad is 777 tonnes.

Take the acceleration due to gravity (g) as 9.8 N/kg or 9.8 m/s^2.

a. Calculate the resultant force on the rocket. It can be useful to draw a force diagram. Ignore air resistance.
Resultant force on rocket = 6.25 MN

b. Calculate the acceleration of the rocket at the moment of launch.
Acceleration = 8.04 m/s^2

Figure 4



↑ Typical launch sequence of an Ariane 5 rocket.

2. Assume the rocket rises vertically for the first twenty seconds. Each EAP booster uses 1.8 tonnes of propellant per second and the EPC main stage uses 0.3 tonnes of propellant per second.

a. Calculate the mass of the rocket after 20 seconds and hence calculate its acceleration at this time.

Mass of the rocket after 20 seconds:
777 000 kg - (2 x 1.8 t x 1000 kg x 20 s) - (0.3 t x 1000 kg x 20 s) = 699 000 kg
Instantaneous acceleration:
Thrust = 13 860 000 kg m/s^2
Weight = 699 000 kg x 9.8 m/s^2 = 6 850 200 kg m/s^2
Resultant force = 13 860 000 kg m/s^2 – 6 850 200 kg m/s^2 = 7 009 800 kg m/s^2
Acceleration = force/mass = 10.03m/s^2

b. In reality the rocket's acceleration at this time would be different to the acceleration you have calculated. Do you think the actual value would be higher or lower? Explain your answer. A new force diagram may help you with this.

As the rocket accelerates through the atmosphere its velocity increases and, as a result, atmospheric drag also increases. This is because the force of atmospheric drag is proportional to the density of the air and also to the square of the velocity. This means that as velocity through the atmosphere increases, atmospheric drag plays an increasingly important role. As a result, after 20 seconds of flight, the effect of the drag force is that the resultant force (thrust – drag - weight) will be less than the resultant force would be without the drag (thrust - weight) and so the acceleration will be smaller than previously calculated. As the rocket continues through the atmosphere, air density reduces progressively and at the same time the speed (and acceleration) of the rocket increases as the weight of the rocket diminishes due to the propellants' consumption in the engine(s).

3. The Ariane 5 User Manual gives two figures for the thrust of the EPC main stage (which runs for nine minutes):
   - 960 kN at sea level
   - 1390 kN in vacuum

   Explain why these figures are different.

   The thrust that a rocket engine produces depends on the velocity of the expelled gases from the combustion chamber. The pressure difference between the gases in the combustion chamber and the surrounding external atmosphere is what drives the exhaust gases out of the combustion chamber and produces thrust. This difference will be maximal in a vacuum. This is why the vacuum thrust is always greater than the thrust at sea level.

→ LINKS

ESA resources

Whoosh bottle – Classroom Demonstration Video (VP01):
http://www.esa.int/spaceinvideos/Videos/2014/07/Whoosh_bottle_-_classroom_demonstration_video_VP01

ESA classroom resources:
www.esa.int/Education/Classroom_resources

Solid and liquid fuel rockets:
www.esa.int/Education/Solid_and_liquid_fuel_rockets

ESA Kids introduction to rockets:
www.esa.int/esaKIDSen/SEMYWIXJD1E_Technology_0.html

Introduction to the Ariane 5 rocket:
www.esa.int/Our_Activities/Launchers/Launch_vehicles/Ariane_5

Ariane 5 resources

Information about the Ariane 5 rocket:
www.arianespace.com/vehicle/ariane-5/

Wikipedia entry for Ariane 5:
en.wikipedia.org/wiki/Ariane_5

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www.esa.int/education

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