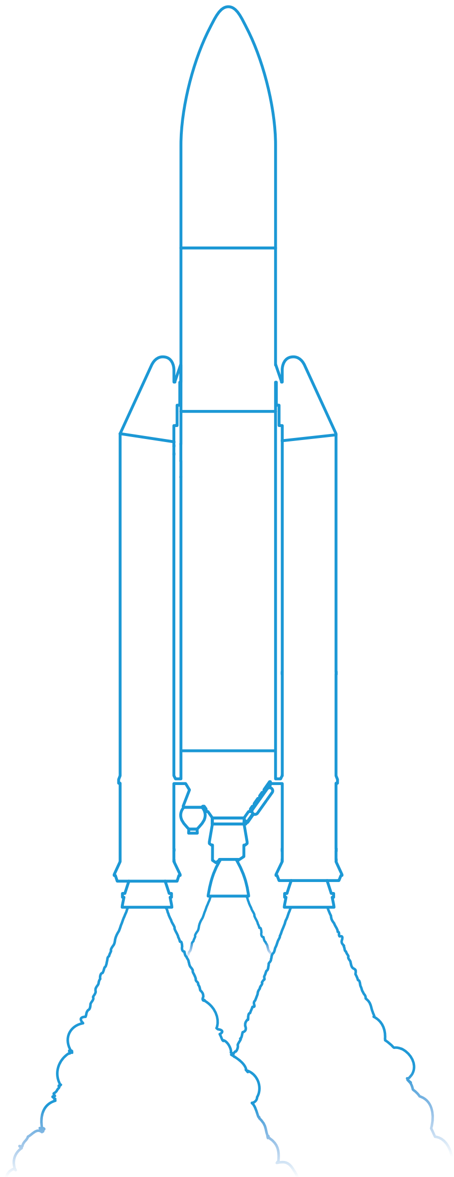
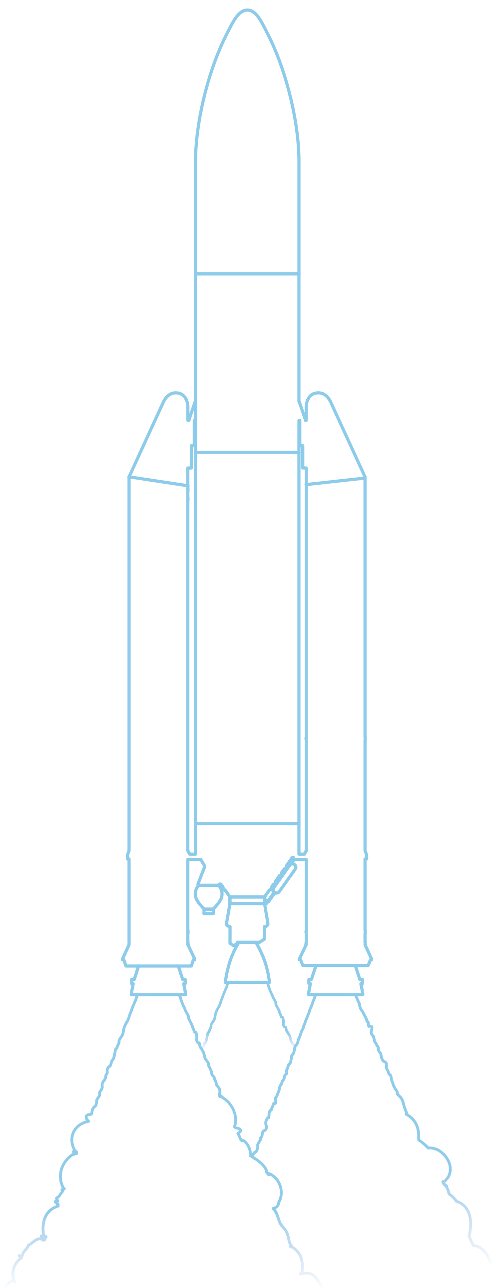
teach with space

→ WHOOSH BOTTLE

Applying Newton's laws to rockets





→ BACKGROUND

Understanding forces is fundamental to appreciating how and why matter in the Universe moves. The effects of forces can be described by Newton's laws of motion.

Newton's first law

If no overall – or RESULTANT - force acts on an object, then the object will either remain at rest, or continue with a constant velocity (i.e. travel in a straight line at constant speed). Forces are required to change the speed or direction of any object.

An equilibrium occurs when the resultant (or net) force on an object is zero. If an object accelerates (i.e changes its direction of motion or its speed - or both), then there must be a resultant force acting on the object.

Newton's second law

The net force acting on a body is proportional to the rate at which its momentum changes: F=ma, where F is measured in Newtons.

Newton's second law addresses how a resultant force changes an object's motion.

Newton's third law

If body A exerts a force on body B, then through that process, body B will exert an equal and opposite force back on body A.

This is often described as "every action has an equal and opposite reaction". Forces occur in pairs, and no object can exert a force on itself in isolation.

In this activity, Newton's laws are applied to rocketry:

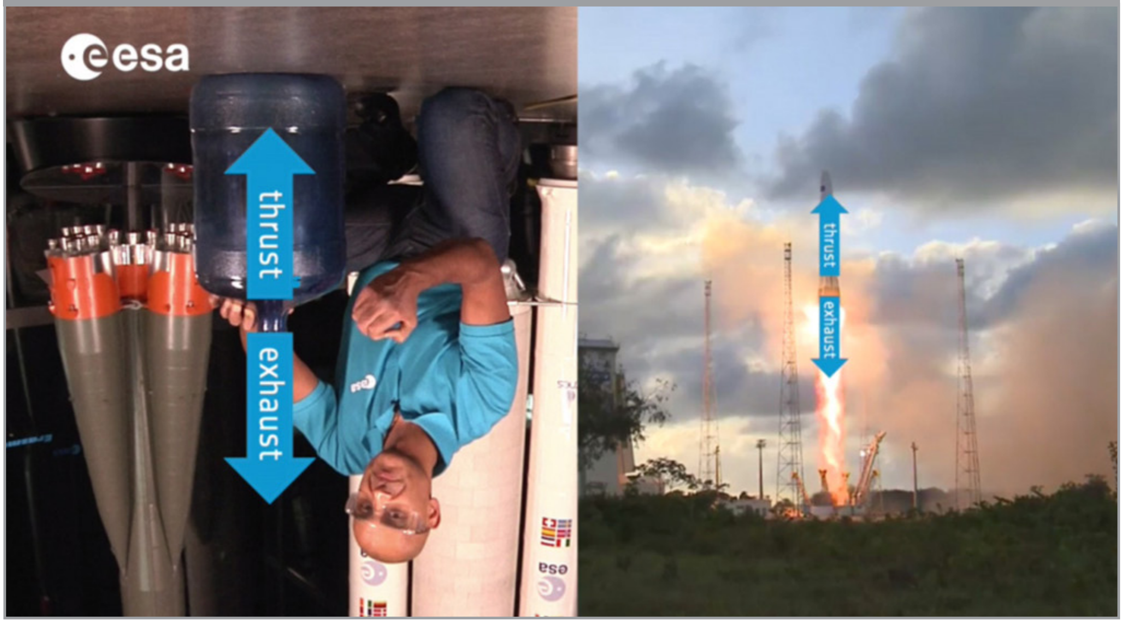
- **Newton's first and second laws:** The resultant force on the rocket (the thrust minus the total of all forces acting in the opposite direction) causes an acceleration, which can be calculated by applying Newton's second law "F=ma" and substituting in the mass of the rocket. During the firing of the rocket stage engine, the mass of the rocket decreases as the products of the chemical reaction are ejected from the engine. This means that for a given stage, the acceleration produced for a given thrust increases with time.

- **Newton's third law:** When a rocket engine expels exhaust gases in one direction, the escaping gases exert an equal and opposite force back on the rocket. This is called the reaction force, or thrust force, produced by the engine. The reaction pushes the rocket upward and off the ground.

More realistic modelling of this concept can be investigated through application of the full version of Newton's second law – force is proportional to the rate of change of momentum. This, combined with Newton's third law, indicates that greater thrust can be achieved by:

a. Maximising the mass of exhaust gases expelled per second.
b. Maximising the exhaust gas velocity.
c. Minimising the time over which this occurs.

Figure A1



↑ To launch a rocket in space there needs to be enough thrust. This is the Whoosh bottle Classroom Demonstration Video that you can find on ESA's Education website.

→ ACTIVITY 1: BURN FUEL, BURN

Rockets have been used for hundreds of years. The first rockets were used in China for fireworks almost 1000 years ago. Nowadays rockets have many other applications, including taking astronauts to the International Space Station, sending probes to space to explore the Solar System, and launching satellites into orbit around the Earth. In this activity a mixture of air and alcohol is ignited inside a plastic bottle, simulating what happens during the ignition of fuel in a rocket launch. You will see a rapid reaction, accompanied by a dramatic 'whoosh' sound and flames, demonstrating the large amount of energy released in combustion reactions.

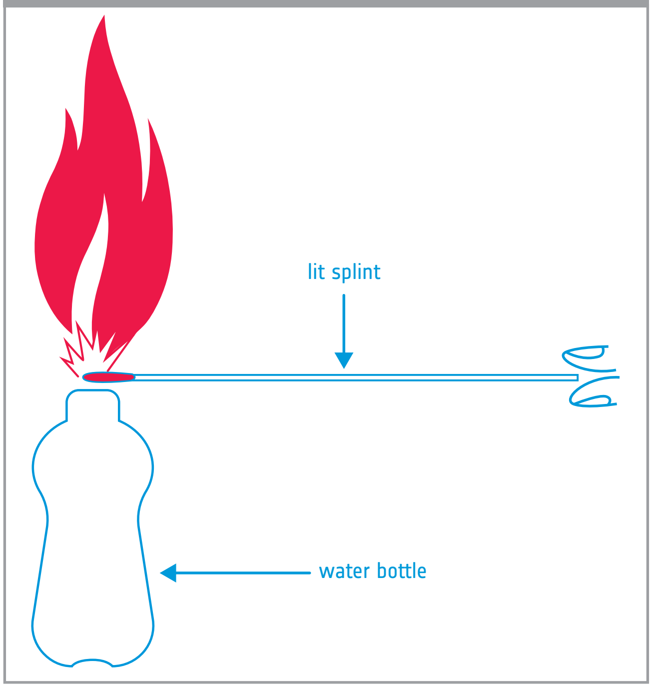
Equipment

- 1 small plastic bottle with lid, such as a 500 ml empty water bottle
- 1 ml of methylated spirit/ethanol (or other chosen fuel)
- Safety glasses
- 1 heat proof mat
- Long matches (only to be used by teacher)

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.
- Do not hold your body over the top of the bottle.
- Follow the general safety control measures in the laboratory.

Figure A2



↑ Experimental set-up

Exercise

1. Put on safety glasses.
2. Remove the lid from the water bottle and ensure the bottle is completely dry.
3. Pour 1 ml of fuel into the bottle.
4. Replace the lid and shake well.
5. If any fuel is left at the bottom of the bottle, pour it out in a safe place, and replace the lid.
6. Stand the bottle on the table on top of a heat proof mat and wait for your teacher. Always keep your table clean.
7. When the teacher is present, remove the lid, stand back, and watch as your teacher puts a lit match to the mouth of the bottle.
8. Observe what happens. Also observe what happens when the other students' bottles are lit.

Discussion

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

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2. The reaction was accompanied by a whoosh sound. Explain where this sound came from.

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3. Considering Newton's third law, identify the forces that act on the bottle during the combustion reaction.

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

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.

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

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

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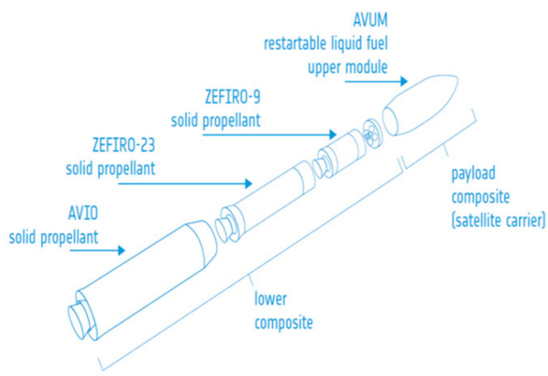
Did you know?

The thrust of a rocket accelerates all of its mass (payload, fuel, oxidiser, and rocket structure). In order to limit the amount of extra mass that is being carried for the whole journey, and thus maximise the acceleration, rockets are often built in multiple stages. Typically, two or more stages will fall away from the craft (significantly reducing the mass) once they have completed their engine burn. Vega, ESA's small launcher, is shown in the diagram on the right. Vega has three solid-propelled stages and one liquid-propelled upper module to control the rocket when it is in orbit.



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

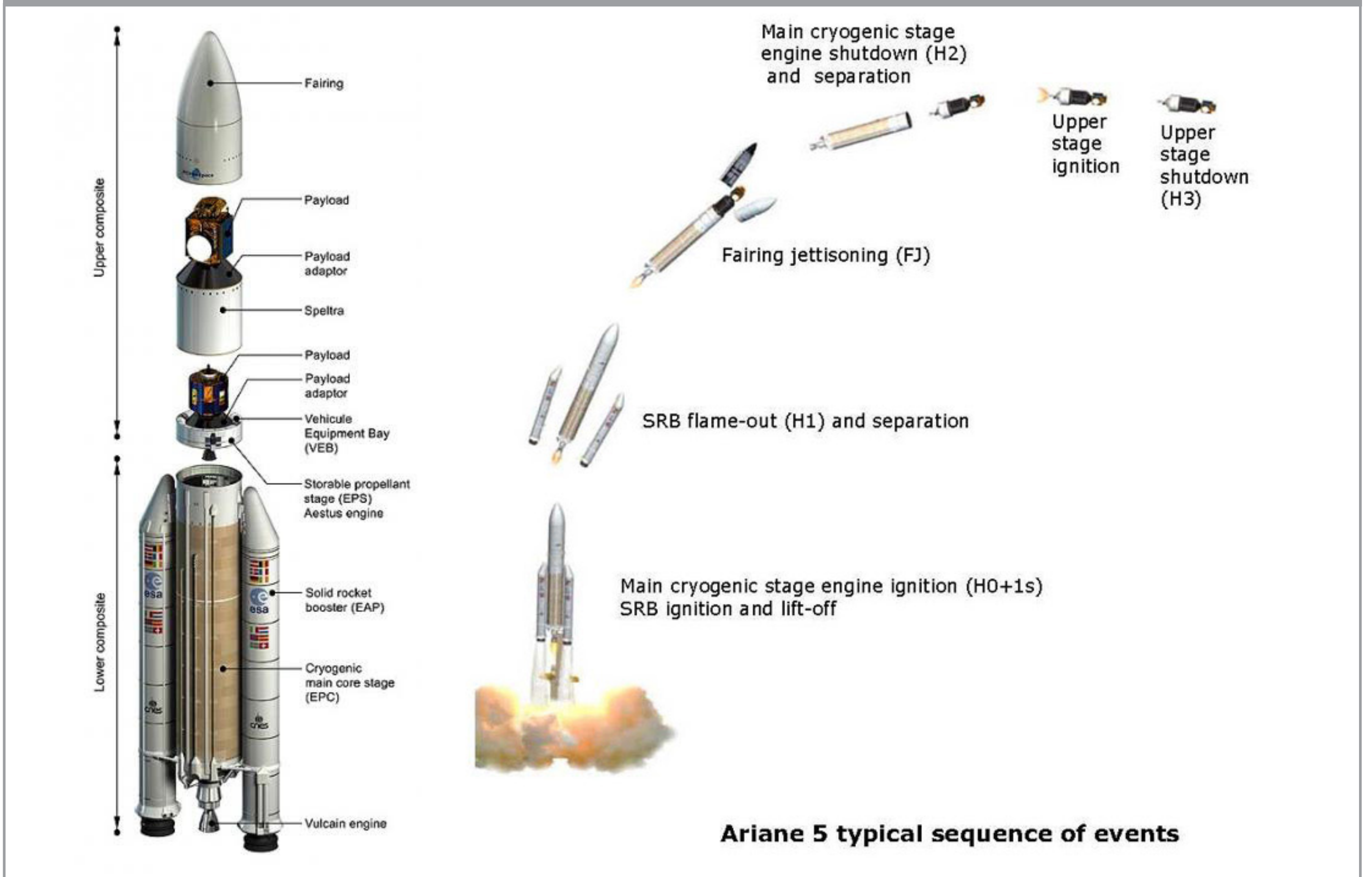
To launch a rocket into space there needs to be enough thrust to counteract gravity. In this activity, you will be an ESA rocket scientist or engineer. You will apply Newton's second law to rockets to calculate the amount of fuel a rocket needs to create the necessary thrust to launch.

Exercise

1. An Ariane 5 ECA rocket is on the launch pad in Kourou, French Guiana. The lower section of the Ariane 5 ECA consists of the main cryogenic core stage (EPC) and the two solid propellant boosters (EAP) (see Figure A3). 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 launch pad is 777 tonnes.

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

Figure A3



↑ Typical launch sequence of an Ariane 5 rocket.

a. Calculate the resultant force on the rocket and its initial acceleration. It may be useful to draw a force diagram. Ignore air resistance.
Calculation:

b. Calculate the acceleration of the rocket at the moment of launch.
Calculation:

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. Ignore air resistance.

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

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.

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.

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