

DEFYING GRAVITY

Teacher Notes

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1. A brief history of space exploration

We have been exploring space for over 50 years, but many of our advances have been as a result of a competition between the Americans and Russians to do things first. It all began with a strange beeping noise [Resource 1.1: file DG1 – Sputnik]. This sound was picked up in America in 1957 and it caused panic. Can your pupils identify its origin? The sound came from Sputnik, which was the first ever satellite to be launched into orbit.

It's hard to imagine that at that time it was the only object in orbit. Since then thousands of satellites have been put in orbit and many are transmitting data backwards and forwards [Resource 1.2: satellites]. Only a few short years later, the Russians were the first to put a human in orbit: Yuri Gagarin went up in 1961. Even though John Glenn went into space a month later, the Americans were caught off guard by the success of the USSR as they had previously viewed them as technically weak.

In response to being beaten into second place, the Americans went on the offensive. President Kennedy announced in the early 1960s that America would be the first to send a human to walk on the Moon. President Kennedy sums up their ambitions [Resource 1.3: file DG2 – JFK Moon speech]. Less than 10 years later, Neil Armstrong became the first of 12 human visitors. There were 6 trips in total, the last in 1972. So, it was only across three years that we visited the moon.

The focus of space exploration moved on and countries began to establish off-world bases: Skylab and Mir were early space stations visited by the USA and Russia respectively and robots were sent to visit far away planets, moons and asteroids. Why do your pupils think we send robots and remote controlled craft whilst we humans stay in orbit? Money is one part of the answer and the high risk to human life is the second part.

[Task 1.1: human exploration of space]

There is a lot of well documented research and news stories on the quest to send humans to Mars. A suggested task or investigation is to collate the scientific reasons why we haven't done it yet and ask them to draw a conclusion as to whether we ever will go to Mars. This could be presented as a written report or a short oral report to the class.

Space exploration has given us the opportunity to look back at ourselves. So we are going to take a look at the Earth from the perspective of the only fully-staffed scientific laboratory currently in orbit: the International Space Station, known as the ISS. It is in orbit 400km above the surface of the Earth and it takes 90 minutes to complete one full orbit, so is travelling very quickly. The purpose of the ISS is to do some scientific research to support future missions, particularly a mission to Mars.

[Task 1.2: journey to the Moon and Mars]

How long was the journey to the Moon? What route did the Apollo spacecraft take? How long will the journey to Mars be?

It took only a few days to reach the Moon, but to Mars it is 6 months one way and the effect on the human body is being studied on the ISS, they are also testing new technologies. Full details of the route to the moon can be found in [Resource 1.4: route to the moon].

Let's put the ISS into perspective.

[Demo 1.1: beach ball Earth]

Using a standard Beach Ball, you can demonstrate the distances involved. On this scale, the ISS would orbit at 1cm from the surface of the ball. You can then take a tennis ball to represent the Moon, this needs to be rolled 9m away from the tennis ball, so your classroom may not be large enough! This can be backed up by showing what the surface of the Earth looks like to those on board the ISS [[Resource 1.5: file DG3 – the Earth from the ISS](#)]. This shows the UK at night and in the north you can see the aurora borealis, the northern lights. You can easily pick out the north coast of France and Paris then the south coast of the UK and London, before highlighting the location of your school.

Whilst the UK has never been officially involved in human spaceflight, there have been British-born astronauts who have flown into space but they had to do things like become US citizens and even then there are only a handful. Apart from supplying Astronauts, the UK space industry is thriving. We build satellites, design spacecraft, and analyse data sent back from distant planets and develop theories to explain what we see in the universe. The space sector has seen continued growth when the UK economy overall has been struggling. The number of jobs directly associated with the industry is around growing all the time. As we continue our success we need more people to continue studying subjects such as physics who then go on to work as scientists and engineers. For more background on the Space industry in the UK you can refer to an overview article in [[Resource 1.6: STEM OnQ](#)].

Curriculum Link Summary

Links to National 5:

- Space exploration

Resources

R1.1: DG1 – this is a recording of the sound that Sputnik, the first ever satellite, broadcast in 1957. It played this for 22 days until its battery ran out and could be picked up easily on the ground if you tuned your radio to the correct frequency.

R1.2: <http://www.onastra.com/2169/why-satellite>

R1.3: DG2 – a short piece from the [JFK Moon speech](#) [YouTube]

R 1.4: <http://www.flightglobal.com/page/Apollo-40th-Anniversary/>

R1.4: DG3 – a time-lapse photography file of the [Earth from the ISS](#) [YouTube]

R 1.6: STEM OnQ <http://www.lfthomas.co.uk/wp-content/uploads/2012/09/STEM-On-Q-Iss-2.pdf>

Demonstration equipment

D1.1: Tennis ball, beach ball.

2. Overcoming Gravity

In order to get into space we need to escape the Earth's gravitational field. This means that we're going to have to do some work to overcome gravity. Now gravity is an extremely hard-working interaction. It's responsible for keeping our feet on the ground, the Moon around the Earth and the Earth around the Sun. It is attractive, meaning that objects move towards each other, but the strength of the interaction depends on the size of the objects (eg, compare jumping on the Earth to jumping on the Moon – you can use the Beach ball and tennis ball again to show the size difference) and that we are being pulled towards the centre of the object, in our case the Earth.

Taking a tennis ball, we can try to throw it up in the air as hard as possible but unless enough work is done, it won't be able to escape from the surface of Earth, but there are ways in which it can be given more energy. It could be hit with a tennis racket, fired out of a catapult or it could have a rocket attached to it.

To know what is going to be the most successful in getting the ball into space, we need to know the work that needs to be done in order to overcome gravity. We measure both the work done and the energy transferred in joules. In order to calculate the work done, we need to know the weight of the object and the distance moved.

$$\text{Work done (J)} = \text{Weight (N)} \times \text{Distance (m)}$$

$$\text{where } \text{Weight (N)} = \text{Mass (Kg)} \times \text{Field Strength, } g \left(\frac{\text{N}}{\text{Kg}}\right)$$

[Task 2.1: getting objects into orbit]

Pupils should calculate the weight of each object, before going on to find out how much work needs to be done to get them to their destination. Calculations done using $g=10\text{N/kg}$.

Object	Mass (Kg)	Weight (N)	Distance to travel (m)	Work done (joules)
Tennis ball	60g = 0.06Kg	0.6	400,000	240 000 J
Soyuz rocket	313,000	3, 130, 000	400,000	1.2×10^{11} J
Mars rover	1,100	11,000	80, 000, 000, 000*	8.8×10^{13} J

*this is an estimation of the distance between the Earth and Mars. Why can this distance range from 60 000 000 000 m to 400 000 000 000 m?

What if we were to send the robot to the ISS and the Soyuz to Mars?

Object	Mass (Kg)	Weight (N)	Distance to travel (m)	Work done (joules)
Soyuz rocket	313,000	3, 130, 000	80, 000, 000, 000	2.5×10^{17} J
Mars rover	1,100	11,000	400,000	4.4×10^9 J

The work done to get the Soyuz to Mars is 2,000,000 times the amount required just to get it to the ISS. Ask the pupils to refer back to task 1.1 and discuss this new information in the context of what they discovered.

The tennis ball example could be run through with the class to begin with. The mass of the ball is 0.06kg and the field strength is due to gravity. What is the value of g ? g is 10 N/Kg. This force acting on the body is 0.6 N. If I want to get the ball into a low Earth orbit of 400 km, the work done is calculated as 240 000 J.

In terms of the method we can use to get the ball into space, let's first take a look at the tennis racket. Andy Murray can serve at 65 m/s. When we calculate the kinetic energy this produces, $KE = 118 \text{ J}$, therefore we need over 2000 Andy Murrays hitting the tennis ball at the same time to get it into low Earth orbit. So, as you probably expected, using something like a rocket is going to be much easier.

It's important that the right amount of work is done to overcome gravity but how do rockets actually do it? Before we look at a rocket, let's consider this skateboard/what else can be used in the classroom?

If someone standing on the skateboard wants to travel across the room, in which direction to they need to make an action? It should be made in the opposite direction to the desired direction of travel. Newton categorised this type of event as his third law: for every action there is an equal and opposite reaction.

How does this apply to rockets?

[Demo 2.1: balloon rockets] Firstly, pass out a few balloons around the class and ask them to blow them up, but don't tie them. You should prepare one for yourself as well. One they are ready talk them through a rocket. The balloon you are holding is the rocket which we have filled with fuel, air in our case, but normally the fuel used is liquid oxygen and hydrogen, which is extremely flammable. Our rockets have an exhaust, that's the hole at the bottom where the air was put into the balloon. Now when the fuel combusts in a rocket, there is a force that is pushing down on the ground through the exhaust, but there is a net force which acts upwards allowing the rocket to leave the ground. Do a 3-2-1 countdown and get your pupils to release the balloons to see this in motion. The balloons fly up towards the roof because air is pushed out of the balloon and the force is such that it acts against gravity. You can then show them the power behind a rocket such as the space shuttle [Resource 2.1: file DG4 – space shuttle launch].

Rockets work very simply: they throw their exhaust out backwards very quickly over a set period of time. As the rocket throws out its exhaust, the exhaust in turn pushes the spacecraft in the opposite direction. In order to produce the required force, the exhaust is very flammable. You can see this very clearly with the footage of the Space Shuttle launch. In a rocket motor, the fuel is an expanding gas: pressure acts in all directions as it expands and because there is a hole in the bottom, there is a net upwards force on the inside of the rocket motor.

[Task 2.2: Balloon rockets].

Thread a straw onto a length of string. Fix the string at each end: one onto the desk/bench, the other onto the ceiling or a clamp. The string should be sitting vertically and not be against anything. The straw should run freely up the string. Each pair/group should have different shapes and sizes of balloons and should be issued with a blu tak payload from the teacher. Taking each balloon in turn, blow it up and fix it to the straw using sellotape. The balloon should not be tied. Sit the payload on the top of the balloon. Using a metre rule, record the distance that the payload moves, record the results in a table. As in T2.2 complete the calculation for the work done for each balloon. What conclusions can be drawn about the balloons that move the payload the furthest? Eg, largest volume of air = greatest amount of fuel should result in furthest movement of payload.

The rockets that go to the space station are travelling very quickly, around 8 km/s, to get into orbit. At this speed it would take just under 12 minutes to reach New York if it launched from Glasgow. The rocket, and all moving objects, have

momentum. This means that the rocket will tend to keep moving in the same direction and it is difficult for objects with a lot of momentum to change their direction.

The pre-launch calculations to decide the engine burn required and when to launch become very important as there isn't room for any errors. As we've seen, more mass means more energy needed to get something into orbit, therefore in addition to sending as little as possible into space, we also want to carry the minimum amount of fuel on our rocket.

If there are no external forces acting on the objects involved in an explosion or collision, we say that the momentum is conserved, but we're going to hear from someone else to explain in more detail.

Richard Garriott is one of 7 Private Space Participants who visited the ISS with Space Adventures. In 2008 he spent 10 days on the ISS. Growing up, Richard always thought he would be an Astronaut. Why? Well his Dad, Owen Garriott was an Astronaut. On the street where he grew up in Texas, all of his neighbours were Astronauts. He went to the Astronaut doctor. However, it was this Astronaut doctor who told him that he had bad eyesight and would never be able to be a NASA Astronaut and there haven't really been many alternatives. Richard went on to have a successful career as a games designer and invested the money he made in space companies, one of them being Space Adventures.

This resulted in his journey to the ISS and his contribution to the start of a new era of human spaceflight. Instead of relying on governments, there are more commercial opportunities to go into space. Whilst there, he filmed lots of different physics demonstrations and in this one he will help us to understand more about conservation of momentum [[Resource 2.2: file DG5 - conservation of momentum](#)].

Curriculum Link Summary

Links to National 5: <ul style="list-style-type: none">• Velocity and displacement• Acceleration• Newton's laws• Space exploration	Links to Higher: <ul style="list-style-type: none">• Forces, energy and power• Collisions, explosions and impulse• Gravitation• Gravity and mass
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Resources

R 2.1: [space shuttle launch](#)

R 2.2: [conservation of momentum](#)

Demonstration equipment

As in section 1: beach ball and tennis ball.

D 2.1: balloon rockets – sellotape, straws, scissors, string, balloons, blu tak, metre rule.

3. Rockets as Projectiles

We've talked so far about what we need to do to overcome Earth's gravity. We know that we need a lot of explosive speed to produce the energy required. However, we have always got in mind. Sometimes we want to send a robot to Mars, which means leaving Earth's gravity, but often we want to put a satellite or spacecraft into a specific orbit and all these things can require different speeds.

To put the object into orbit, and indeed to stay at that orbit, it is important to get the launch speed correct. Too slow and it won't get to where you want it and so fall back to Earth, too fast and it will overshoot. So how exactly do we do that? We need to start thinking of our rockets more like projectiles than something that just goes in a straight line upwards.

Sir Isaac Newton came to the understanding that you could fire a projectile in such a way that you could overcome Earth's gravity near the surface but still take advantage of gravity above the Earth. In fact, at the orbit of the International Space Station, the strength of gravity is roughly 90% of what it is on the surface.

[Task 3.1: rockets as projectiles]

We are now going to try and fire projectiles so that they hit the right target. In our case, we want to get into a set orbit. Issue each pair with their target sheet (DG 11.pdf) and catapult building instructions (DG 12.pdf). The aim is to get to the orbit of the International Space Station. That means they need to hit the white area in the middle. If they hit above, they're travelling too quickly and have overcome Earth's gravity. If they hit the red/grey area below, they aren't travelling fast enough and have fallen down through Earth's atmosphere to the surface.

This exercise can be extended by using Tracker to analyse the trajectory of the catapult and draw conclusions.

[Resource 3.1: file DG6 – rockets as projectiles]. You can recreate what the pupils have been doing. Imagine your catapult is sitting on top of the Earth's highest mountain. On your first attempt you don't quite draw the catapult arm back enough and the projectile falls back to Earth (this is what happened when you hit the red targets). Next time, you pull the arm all the way back to the ground and use maximum energy. This time it's travelling fast enough so that it overcomes Earth's gravity altogether and heads off to Mars. Lastly, you get the balance just right so that you hit the white target, this indicates the orbit of the ISS so your rocket makes it into circular orbit around the Earth.

OK, so we're in orbit. When you throw your ball or launch your spacecraft at the right speed it will travel in circular motion above the Earth. Along with the ISS, many different objects are in orbit above the Earth. How do these objects stay in orbit when their interaction with gravity is such that it is being pulled back down to the surface? If it's moving fast enough, or has enough momentum, then the Earth's horizon falls beneath the object more quickly than it is pulled to the centre. The objects can stay in orbit because as they fall back down to the surface of the Earth, the surface curves away from them. If they slow down the Earth is not going to fall away at the same rate, so they come back to the surface.

The key thing at this stage is that the pupils realise that mass impacts on the amount of energy required to overcome gravity, but it is ultimately the destination that determines the speed that the rocket travels at. This in turn means that momentum is an important consideration so they can say that the rocket needs to achieve the correct speed *OR* momentum to get to the chosen destination.

Curriculum Link Summary

Links to National 5: <ul style="list-style-type: none">• Projectile motion• Space exploration	Links to Higher: <ul style="list-style-type: none">• Motion: equations and graphs• Forces, energy and power• Collisions, explosions and impulse
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Resources

R 3.1: file DG6 – rockets as projectiles. These slides contain animations showing what is happening when the hit the different coloured targets.

Demonstration equipment

Items for task only.

4. Off-world living

When an object is moving in a circle at a steady speed, the direction of its motion and its velocity is constantly changing. A force towards the centre of the circle is required – Newton's 2nd law – this is called the centripetal force and is supplied by gravity.

[Demo 4.1: centripetal force.]

You can demonstrate this idea to your class using something like this <http://www.youtube.com/watch?v=56QC14lg4EY> I have made a similar basic platform that can be used with a cup of water and it is very simple to replicate, although I would recommend practicing outside before taking it into the classroom. In fact, I go a bit further in my use of the platform in that I practiced swinging it around my head: <http://youtu.be/VtnJFy21gQQ>.

Now that we have overcome gravity and gotten ourselves into orbit at the International Space Station, what does it actually feel like to be in orbit around the Earth? The objects that are in orbit around the Earth are essentially falling in that orbit. Whereas objects that fall on Earth reach the surface, the ISS falls continuously but never reaches the surface of the Earth due to its speed/momentum. We know that at the orbit of the ISS, gravity is still an important interaction. In fact, even at this distance of 400km the field strength of gravity is still 90% of what it is on the surface.

If an object falls on Earth, there are different stages of falling that it goes through. Let's take ourselves over to New York and the Empire State Building. What happens if, once we are in the lift, the cable snaps and the car begins to fall? What will you experience inside that lift?

As you accelerate you will experience apparent weightlessness, but due to the momentum you are carrying, they are likely to be the last things you experience...so enjoy it! [Resource 4.1: file DG7 – astronauts experiencing weightlessness]. We saw in the clip with Richard that they experience weightless on the ISS. They are falling continuously. The astronauts in the ISS fall with it.

If you've ever been on a roller coaster, you may have experienced apparent weightlessness briefly, usually signified by your stomach feeling like it's dropping and you may have noticed you came out of your seat slightly, it's a very strange sensation. Try to imagine what it feels like to fall constantly. Some astronauts experience travel sickness on the ISS and there's no escape as some of them spend 6 months in orbit.

[Task 4.1 Eating, sleeping and living on the space station.]

There is a wealth of information available about what it's like to live in space. A good starting point for a pupil investigation would be based on films from the ISS. [Resource 4.2: living off-world].

Curriculum Link Summary

Links to National 5: <ul style="list-style-type: none">• Acceleration• Newton's laws• Space exploration	Links to Higher: <ul style="list-style-type: none">• Motion: equations and graphs• Forces, energy and power• Gravitation• Gravity and mass
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Resources

R 4.1: astronauts experiencing [weightlessness](#)

R 4.2: living off-world - <http://www.nationalstemcentre.org.uk/elibrary/resource/3932/eating-sleeping-drinking-and-living-in-space>

Demonstration equipment

D 4.1: centripetal force

Rope, stiff platform (not cardboard), cup, water, scissor, tape.

5. Solar System Exploration

It used to be the case that only governments could send people into space. In recent years that has all changed and there are now many private companies building spacecraft to send people, instruments and supplies into space. These include Space X – run by PayPal founder Elon Musk – and Virgin Galactic – part of British entrepreneur Richard Branson's group of companies.

With this change, there is the expectation that more scientists and engineers will be needed to go into space to work. Imagine getting into your rocket, launching to your lab in space and staying there for a while before coming home. The ISS isn't a hotel, it's a scientific laboratory. As was Mir and Skylab before it. Scientific research carried out on the ISS can have commercial value and companies will pay in order to have their experiments carried out there. In fact, one recent Private Space Participant, Richard Garriott, paid for some of his trip by doing research and he believes that entrepreneurs are vital to expand our work in space.

However, it is likely to be some time yet before we visit far away destinations such as Mars. In terms of the scale of the solar system, us humans haven't gotten very far. The Russians made it to Earth orbit in the 1950s and the Americans made it to the Moon in the 1960s and 1970s - Neil Armstrong being the first of these pioneers. Since the breakthrough of going to the Moon, humans have not strayed further than Earth orbit. At the moment, the ISS is staffed 24 hours a day, 365 days a year by a crew of 6 and in total less than 500 people have been into space.

However, due to space exploration we are able to take a look at ourselves from a different perspective. You can start by showing your pupils pictures from the furthest place we have visited – the Moon [[Resource 5.1: file DG8 – Earth images](#)]. Beyond this point in space we haven't sent humans, but we have sent robots and remote controlled spacecraft to explore. Voyagers I & II launched in 1977 to explore Jupiter, Saturn, Uranus and Neptune. 34 years later these amazing craft are still under the control of NASA and are exploring the outer Solar System [[Resource 5.2: file DG9 – Spacecraft top trumps](#)].

[Task 5.1: Spacecraft top trumps]

Based on the three cards supplied, ask your pupils to choose another space mission and create their own cards. Below is a list of missions. Once there is a sufficient number, they can play the game. [[Resource 5.3: template top trumps card](#)].

Mission suggestions:

Mars Curiosity rover, Chandra (X-ray observatory), Hubble telescope, Lunar Reconnaissance Orbiter, Mars Global Surveyor, Pioneer. [[Resource: 5.4 Mission list](#)]

The next image in R 5.1 is called the Pale blue dot. This is a portrait of Earth taken by Voyager in 1990 from a distance of 332 light minutes or 6,000,000,000 km – beyond Neptune.

Almost as soon as Voyager launched, work began on Cassini-Huygens and had a different mission. Designed to explore Saturn and one of its moons, Titan, it launched in 1997 and arrived at Saturn in 2004. It's there now and is taking images. This mission will be explored in greater detail in the next section.

The third image in R 5.1 shows Saturn when the Sun was sitting directly behind. This is in fact several images taken and put together. It is a beautiful image and shows Saturn and its rings in great detail. However, if we focus on one section – move

onto the next image – there is something in this picture that wasn't expected. The bright dot that is hanging out by itself on the right hand side of the picture is the Earth again. This time, this picture wasn't a deliberate portrait. Instead, it was taken by accident and it took the scientists at mission control a few minutes to confirm what it was. It has then been taken and blown up to show more detail in the top left hand corner. Here, you can see the Moon just appearing around the top left hand side of the Earth. So this is what we look like from Saturn. In earlier sections we discussed the impact that mass has on how much energy is required to overcome gravity. This means that technology is often miniaturised and this was the case with the camera system on the Cassini spacecraft. Ask your pupils what kind of Megapixel count they have on their phone. The Cassini images are taken with a 1 Megapixel camera, which seems outdated to us now, but the technology used to build the camera on Cassini has made its way into wider use.

There are thousands of people involved in missions like Cassini. From the people who design the spacecraft, those who build the instruments, the people who are responsible for launching it and operating it whilst in space and finally there are the people who analyse the data sent back.

Task 5.2: careers in space

Carry out research into the different roles that form part of a space mission.

Curriculum Link Summary

Links to National 5:

- Space exploration

Resources

R 5.1: file DG8 – Earth images

R 5.2: file DG9 – Spacecraft top trumps [PDF and Powerpoint]

R 5.3: file DG10 – Spacecraft top trumps template card [PDF and Powerpoint]

R 5.4: comprehensive mission list <http://www.nasa.gov/missions/>

Demonstration equipment

N/A

6. Useful resources and events for teachers

Resources:

[Canada Arm simulator game](#): take control of the robotic arm on the ISS in this game

[Earth Camera on the ISS](#)

[ESERO: the UK Space Education Office](#)

[Explore NASA's home and city app where you can "trace space back to you!"](#) - it highlights where NASA work has impacted in the home and elsewhere.

[Faulkes Telescope](#)

[Interactive satellite tracking app from NASA](#) – find out when the ISS is passing above and give it a wave.

[ISS Primary Education Kit](#)

[National Schools Observatory](#)

[National STEM E-library](#)

[Pupil research briefs](#) – suggestions for research investigations to be run on Astro topics based on real research.

[Rockets and Projectiles](#) - if you would like to go into more detail on the rocket side, the Gatsby Science Enhancement Programme have an excellent set of resources available at the link above. For example, it includes how to use compressed air rockets in class investigations.

[SCRAN](#) – database of free resources for schools, includes many astronomical and space missions.

[Some responses from Command Hadfield to FAQs about the ISS and being in space](#)

[Space Hack: directory of ways to get involved with space exploration](#)

[Stellarium](#) Free observing software shows the night sky where you are.

Events for teachers:

[ESA Summer Workshop](#)

[Goldsmiths Astrophysics Course](#)

[JWST CPD](#)

[SSERC Summer School](#)

[UK Space Conference, Glasgow](#)

[ESERO Teachers' Conference](#)