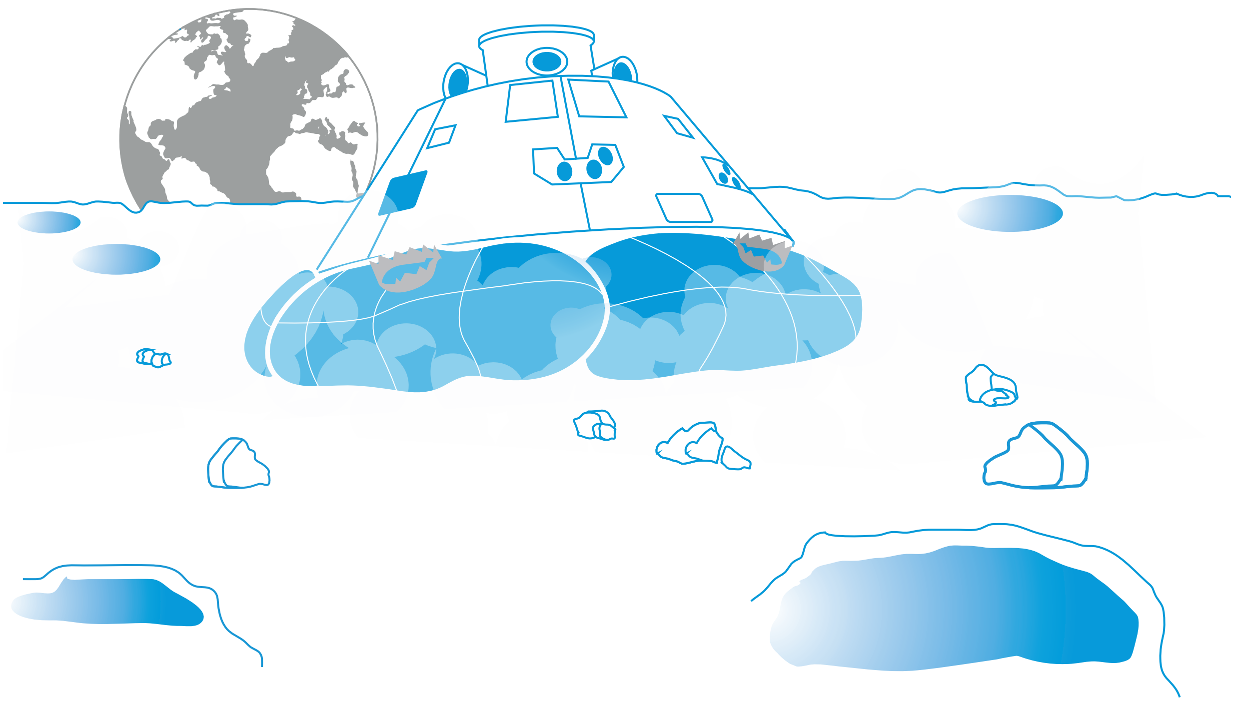
Physics | P37

teach with space

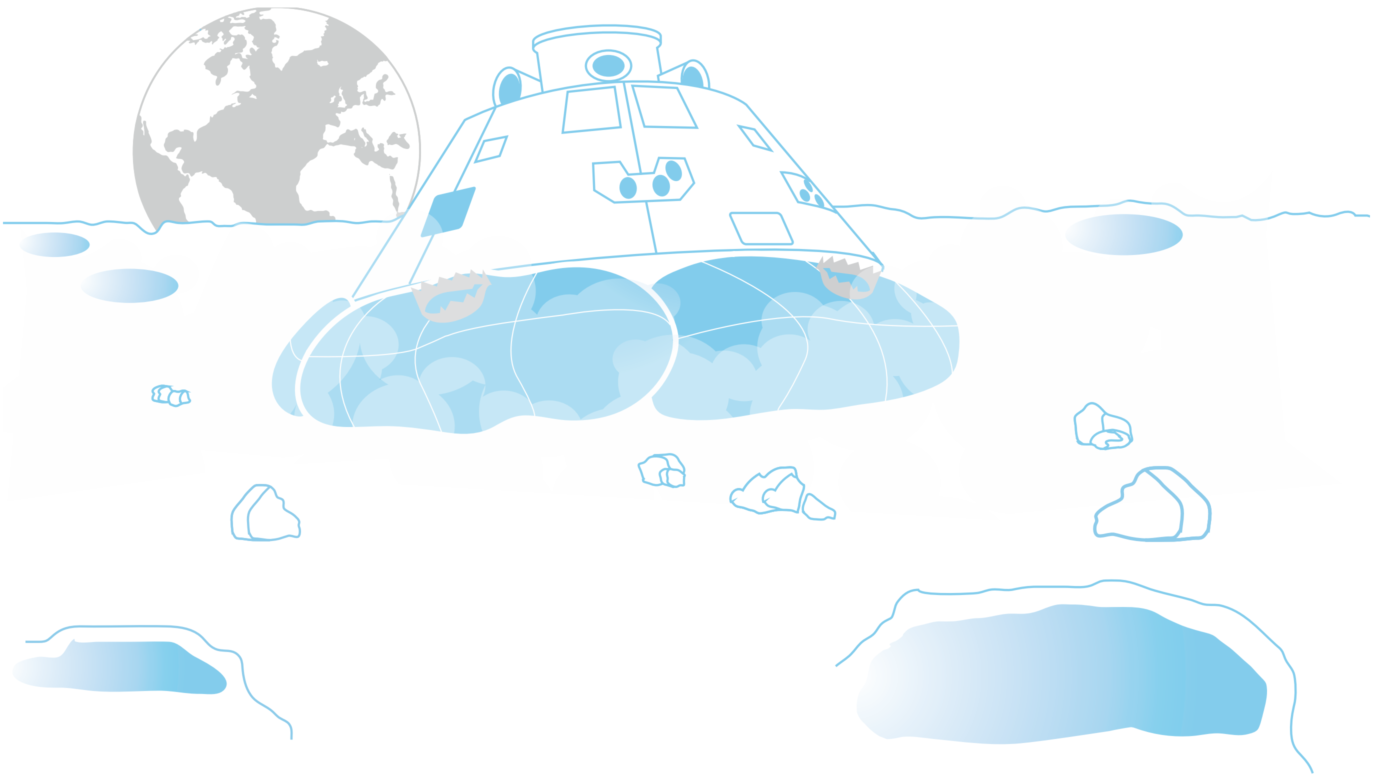
→ LANDING ON THE MOON

Planning and designing a lunar lander



teacher guide & student worksheets

European Space Agency



Teacher guide

teach with space – landing on the moon | P37
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→ LANDING ON THE MOON

Planning and designing a lunar lander

FAST FACTS

Subject: Physics, Mathematics, Economics

Age range: 14-16 years old

Type: student activity

Complexity: medium

Teacher preparation time: 1 hour

Lesson time required: 2 hours and 30 minutes overall

Cost: low (0-10 euros)

Location: classroom and outdoors

Keywords: Physics, Mathematics, Economics, Moon landing, Gravity, Friction, Force, Acceleration, Velocity, Newton's laws, Budgeting, Risk-analysis

Brief description

In this set of activities, students will plan, design, and build a landing module to secure the survival of the crew (in the form of an egg-naut) landing on the Moon. They will explore which factors should be considered when landing on the Moon, in comparison to landing on Earth. In the design of the lunar lander, students must take risk factors and budgeting into account.

Learning objectives

- Identify the forces involved in landing on the Earth and Moon surfaces.
- Understand the relationship between mass and gravitational force.
- Solve a problem using Newton's second law of motion.
- Design a project taking into account a budget and risk management.
- Working in a team under time and money constraints.

→ Summary of activities

Summary of activities					
	Title	Description	Outcome	Requirements	Time
1	Design and build a lunar lander	Design and build a lunar lander. Performing a risk assesment study and a design study.	Learn to design a project with a fixed budget and requirements. Complete a risk assessment and a design study. Build a lunar lander.	None	60 minutes
2	Test your landing module	Test of the lunar lander. Analyses of the results.	Test the lander and collect data. Calculate the acceleration and velocity during the landing.	Completion of activity 1.	60 minutes
3	Landing on the Moon	Comparison between landing on the Earth and the Moon.	Learn about the differences between the Moon and Earth. Calculate the gravitational acceleration and gravitational force.	Completion of activity 2.	30 minutes

→ Introduction

In 1969, Apollo 11 became the first manned mission to land on the Moon. After a four-day trip from Earth, the lunar lander, named Eagle, detached from the command module orbiting the Moon and touched down in Mare Tranquilitatis, a relatively smooth and level area. The lunar lander was manually controlled to avoid boulders and craters. "Houston, Tranquility Base here. The Eagle has landed." These words marked a new era of human exploration.

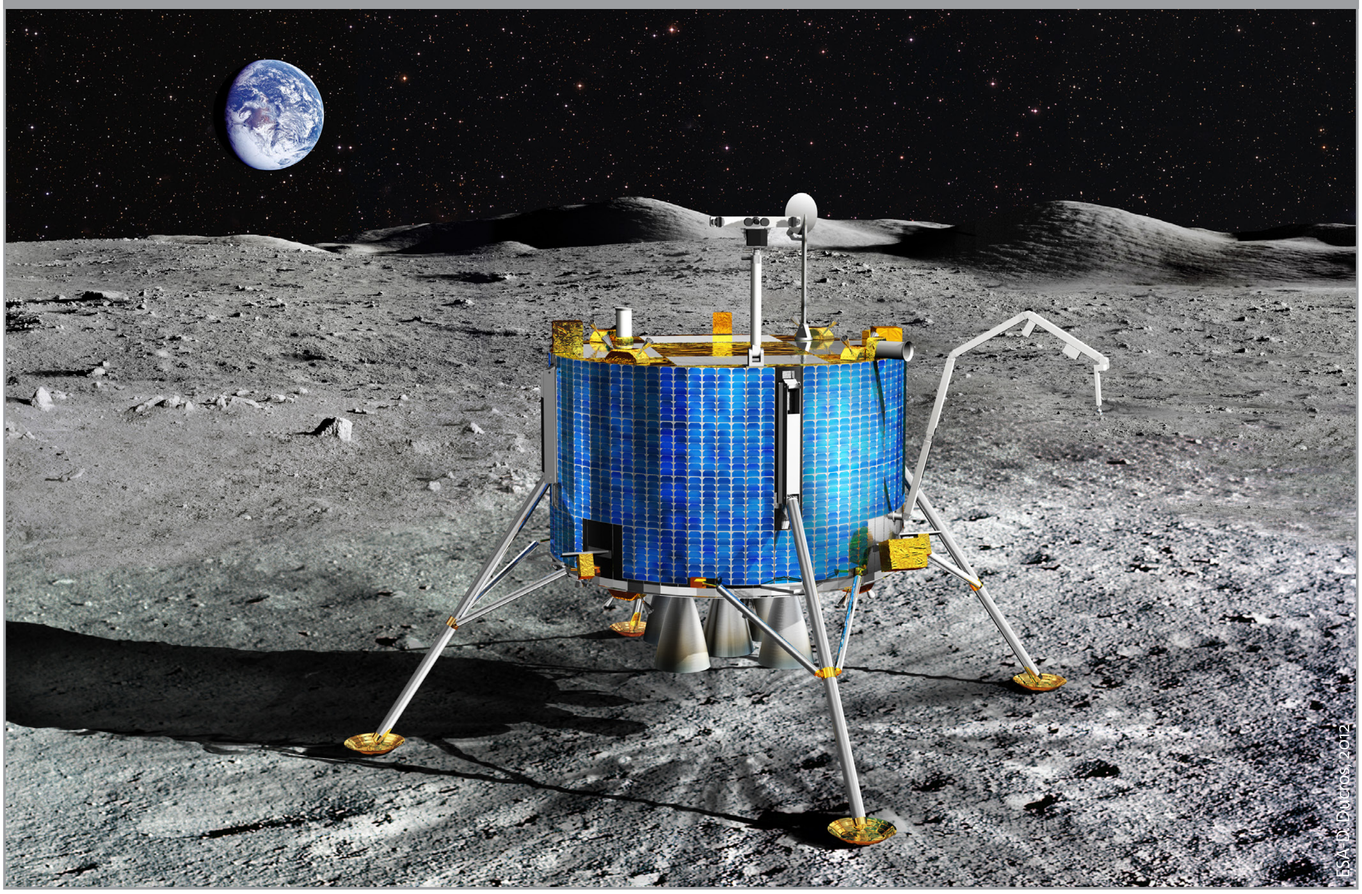
Apollo 12, the second manned mission to land on the Moon, was an exercise in precision landing; most of the descent was automatic and the precision landing was of great significance because it increased confidence in landing at specific areas of interest.

Descending to the lunar surface is one of the most critical and difficult phases of a lunar landing. The spacecraft needs to decrease its speed from 6000 km/h in lunar orbit to a few km/h for a soft touchdown. Landing sites of interest for exploration are often hazardous, with craters, rocks and slopes, and therefore, difficult to access.

Only 12 people have walked on the surface of the Moon and the last time was in 1972.
The European Space Agency, in collaboration with other partners, is planning to return to the Moon with robotic and human missions in the next decades.

In this set of activities students will design a lunar lander and learn about some of the challenges of space exploration.

Figure 1



↑ Artist impression of a lunar lander.

→ Activity 1: Design and build a lunar landing module

In this activity, students will design and build a lunar landing module using simple materials. The objective is to design a lander that can safely land an egg-naut on the surface of the Moon. In their planning, students must consider the risks involved in a manned lunar lander mission and perform a risk assesment study and a design study.

Equipment

- Paper
- Student worksheet printed for each group
- Straws
- Marshmallows
- Cotton-balls
- Popsicle sticks
- Plastic bag
- String
- Sticky tape
- Scissors
- balloons
- Eggs – 1 per group of students
- Scales

Exercise

Divide the class into groups of 3 to 4 students. Distribute to each group the student worksheets. Explain the mission and its requirements to the students. Prompt each group to design a manned lunar lander for the European Space Agency (ESA). They can keep their designs secret from the other groups or they can chose to form collaborative teams and help each other. Each team is still expected to present their unique design.

Before the students start their work, guide them to some of the major questions they should take into account. Ask the students what is important to think about when landing on another celestial body. For example, the distance to the destination, the composition of or lack of atmosphere, the importance of landing in the right spot, the angle of approach, etc.

Provide the students with the list of materials and their costs (Annex 1). To promote efficient planning, materials acquired after the initial design phase should cost 10% more. Each team has a budget of 1 billion €. This budget should cover the costs with the training of the egg-naut (300 million €), the launch (1 million € per gram) and the materials. The list of materials and available budget can be adjusted to make the activity more or less complex or at a determined time a budget cut (or raise) can be introduced.

Design phase:

Before starting construction, the students should prepare a risk assessment study, using the student worksheet template. In risk management, you assess both the probability and the impact of a risk occuring. Risks occur in everything from the planning of the design, to the construction, to transportation and to training of the crew. In the student worksheet, students will find a risk assessment matrix and a list of potential risks for this mission. The use of such a matrix is a common way to analyse and organise risks in many different professional fields. Students should fill in the listed risks in the matrix and brainstorm if there are any risks they have not taken into consideration. They should pick three of the most critical risks and devise mitigation strategies.

The students should brainstorm solutions and try to design the safest lander, within their budget. The students should draw an accurate sketch of their idea and prepare a budget for the proposed module, using the student worksheet template. Explain that this process is comparable to designing an actual space mission; all materials and systems used must be carefully planned, justified, and budgeted.

Construction phase:

Now have the students build their lander. They will probably realize that some decisions they thought possible do not have the expected result. To increase difficulty, include an additional charge of 10% in the materials if the students wish to change their design.

Students should name their module (and their egg-naut). In the end, groups will have to weigh their lander and egg-naut to estimate the launch cost. The final cost must be below 1 billion € and it should include the training of the egg-naut, the launch, and the materials used to build the lander.

Results

Below we show an example of how to fill in the risk assessment study. How the students rate the risk can vary and depends on their perception of the mission.

		Consequences				
		Insignificant	Minor	Moderate	Major	Catastrophic
Likelihood	Almost certain		The lander is damaged during testing	We do not land at the appointed landing site		
	Likely		Another company (group) has a more efficient and/or cheaper design	We get delayed	There are unexpected changes to the requirements	The egg-naut does not survive
	Possible		The lander is damaged during transportation	The lander becomes very heavy	There are unexpected changes to the budget	The lander is damaged during the final landing
	Unlikely				Some materials become too expensive	Continuously changing the design means the lander cost too much to build
	Rare				Some materials become unavailable	

Risk 1: The egg-naut does not survive
Mitigation plan: Build the lander with contingency: do not rely on only one mechanism to secure the landing. Test the drop with increasing altitude before the final test drop. Test the lander without the egg-naut first.

Risk 2: Continuously changing the design means the lander costs too much to build
Mitigation plan: Design the lander with money to spare before beginning construction. Apply for additional funding from other sources.

Risk 3: There are unexpected changes to the requirements
Mitigation plan: Adaptable design and redundancy. Not relying on one single technology or mechanism. Design the lander with money to spare before beginning construction

Discussion

This activity should create awareness about the importance of identifying and understanding risks, their likelihood of occurrence, and, importantly, their consequences. Students should realise the immense importance of planning and budgeting accordingly in a (space) project.

You can use this activity to discuss some of the dangers that exist in space exploration. In class, discuss how to evaluate the risk of losing the life of an astronaut compared to the cost of the lander. Should space exploration in future be done only by robots?

Before you initiate Activity 2 (testing the lander), make sure to have a clear definition of what is considered to be a "surviving egg-naut". Should you allow the egg to have any cracks? What defines a successful mission?

→ Activity 2: Test your landing module

In this activity, students will test if their landers survive a vertical drop, keeping the egg-naut safe. They will describe the landing conditions and keep track of other factors that can influence the results. Optionally, students can film the drop and later use a video analysing tool to examine the acceleration.

Equipment

- Student worksheet printed for each group
- Self-built landing modules including egg-nauts (from Activity 1)
- (optional) Camera/camera-phone and tripod (see annex 3)
- (optional) Video tracking program (see annex 3)
- (optional) Computer or smartphone

Exercise 1

Before starting the tests, the students should write down the landing conditions (hardness of the ground, weather conditions, etc.). It is important to have similar conditions for each drop. Discuss with the students the importance of not changing several variables simultaneously.

Mark a test-landing site on the ground. You can mark a cross with tape on the floor, or draw a target as a bullseye and rings marking the distance from the centre. Record the results of each drop (table in Annex 2). Optionally, for the successful lunar landers, you can perform tests at different heights. The surviving landers should have a structure that softens the initial impact (such as cushion) or may have multiple mechanisms that dissipate the impact energy.

You can chose a winning lunar lander based on the following criteria:
- Height of the drop that the lander could withstand
- Distance from landing target
- Cost of the lander
- How well the final lander followed the initial design and budget
- Overall teamwork, planning, and communication of the group

Ask the students to present their project to the class. They should analyse how well their plan worked and what they would do differently now that they know their final results. Students should discuss also which external factors influenced the drop, for example weather conditions (strong wind, rain etc.) or the egg landing on different materials (asphalt, sand, grass etc.).

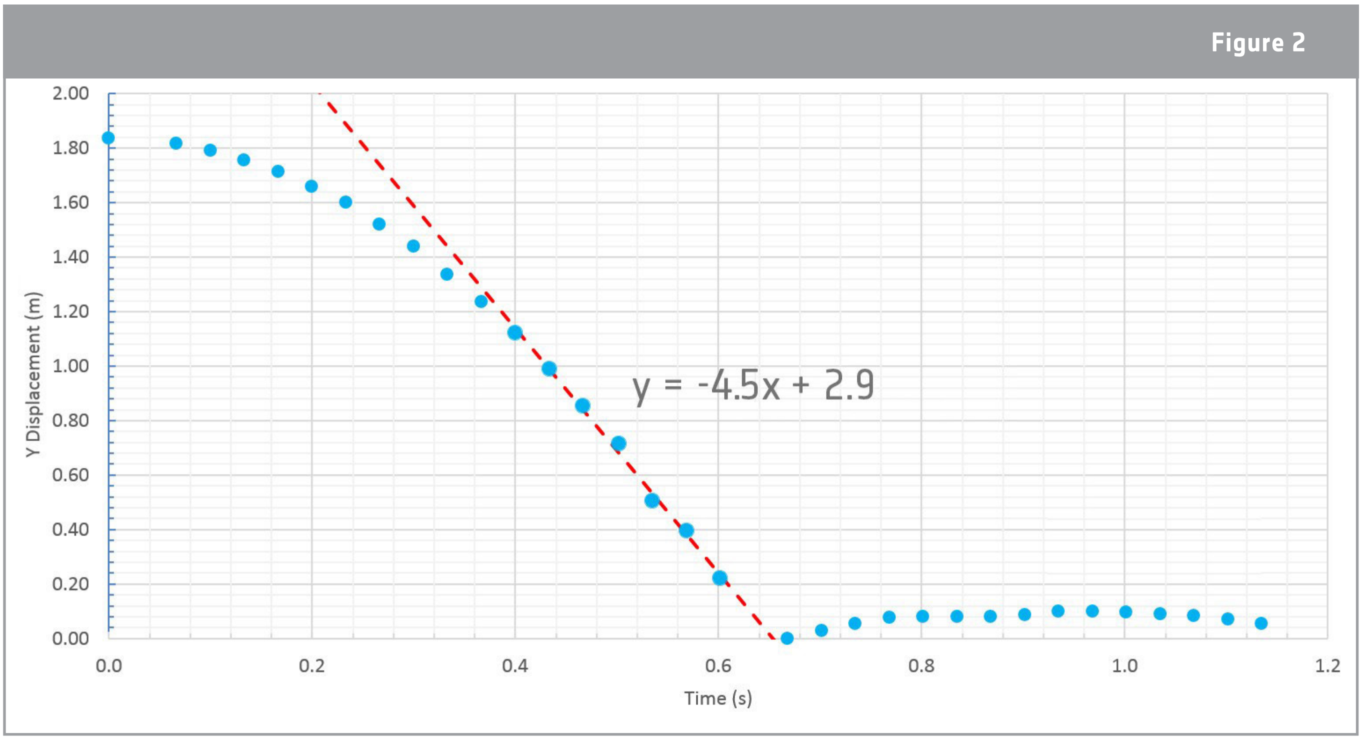
Exercise 2

For Exercise 2, you will need the position and velocity, as a function of time. For detailed instructions on how to measure these parameters, see Annex 3. Alternatively you can use the sample data provided in Annex 3, Table 1.

In this exercise, students will analyse the velocity and acceleration during the drop(s). As an example we will use the data from Table 1 in Annex 3. Each student will need a graphing calculator, or a computer/smartphone with a program like Excel.

1. Calculating impact velocity on a Displacement in the y-direction vs. Time graph:
   To calculate the approximate impact velocity of the lander, students can first plot the displacement of the lander in the y–direction as a function of time. Then do a linear regression analysis of the data, before the lander hits the ground (including only the 10 to 5 last data points before impact). The slope of this linear regression will correspond to the approximate impact velocity. If the lander has not reached terminal velocity the lander will still be accelerating and this method will be only an approximation.

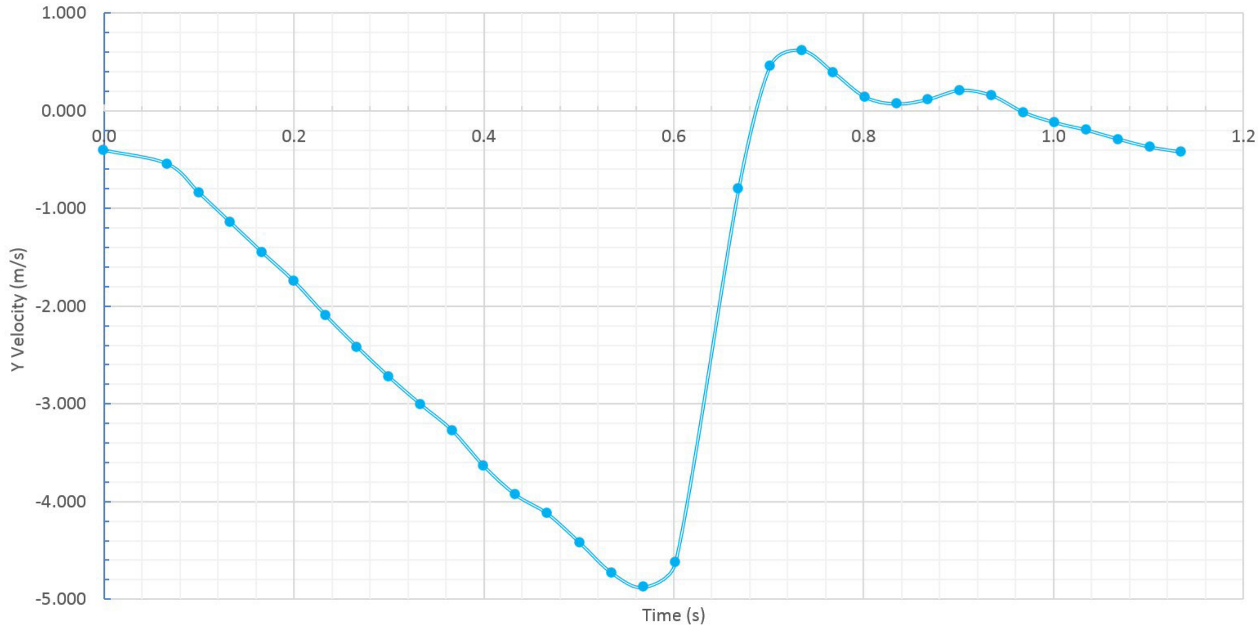
   In the example graph (Figure 2), the impact velocity is approximately 4.5 m/s.



↑ Displacement in y-direction vs. Time.

2. Obtaining impact velocity on velocity in the y-direction vs. time:
   Another method of finding impact velocity is to plot velocity in the y-direction as a function of time. The approximate impact velocity can be easily observed on this graph as the point at which y-velocity flips direction. In Figure 3, we can see that the lander impacts the ground with a velocity between 4.8 and 4.9 m/s, which is approximately the same velocity calculated in question 1. The lander's velocity should not decrease until it reaches the ground (unless it is using a system like a parachute, which is not the case for the sample data). The variations in velocity of the data points close to the point of impact can be due to uncertainty in the measurements.

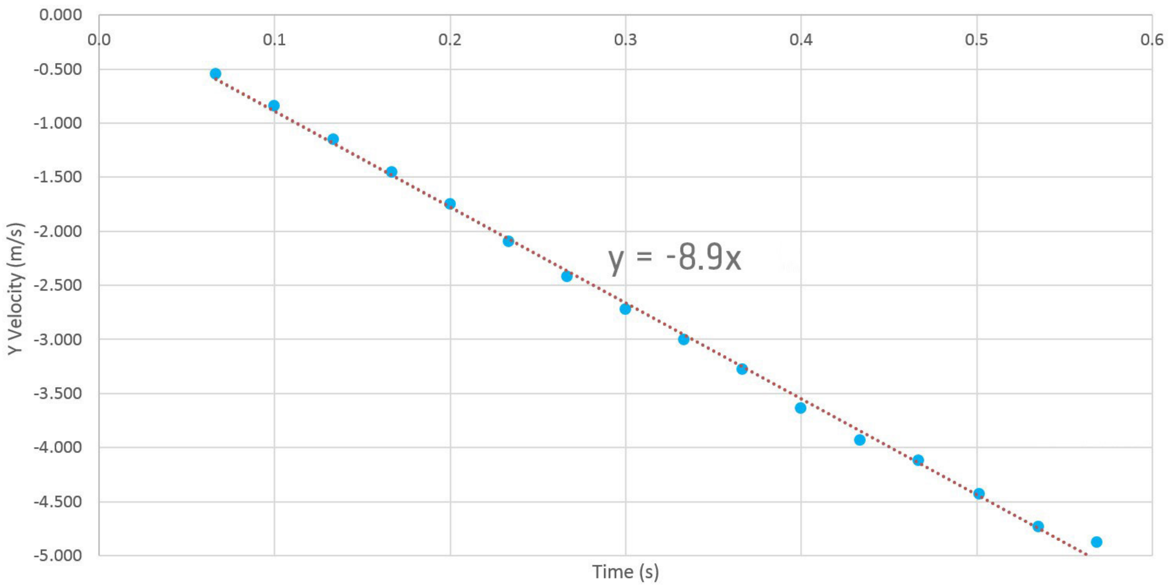
Figure 3



↑ Velocity in the y-direction vs. Time.

3. Calculating acceleration on a velocity in the y-direction vs. time graph:
   To calculate the acceleration of the lander, the students can do a linear regression of the velocity in the y-direction as a function of time, before the point of impact. The slope for this linear regression will correspond to the acceleration of the lander. Using the example data in Figure 4, the acceleration in the y-direction can be calculated as y= - 8.9 x m/s^2.

Figure 4



↑ Linear regression to the Velocity in the y-direction vs. Time data before the point of impact.

4. The impact of drag on the acceleration:
   Due to the presence of the atmosphere the drag force acting on the lander will lead to deceleration. The drag force depends on the square of velocity. If the lander had been dropped from a much higher point, students would be able to measure that the lander reaches terminal velocity (constant velocity) when the drag force equals the weight.

→ Activity 3: Landing on the moon

In this activity, students will compare landing on the Earth with landing on the Moon. They will investigate the different factors influencing the landing in both locations and the forces diagram. Further, the students will re-iterate the design of their lander based on what they have learned during the testing.

Exercise

As introduction to Activity 3, discuss the differences between the Moon and the Earth. Which factors will influence the landing in each case? Guide the students to debate factors like the importance of the location and type of landing site and the angle of descent.

1. Ask the students to list 3 factors that can influence the landing on both places. Here are some examples:

Landing on Earth	Landing on the Moon
1. The atmosphere 2. The landing site 3. The re-entry velocity 4. The re-entry angle 5. The weather	1. The landing site 2. The location on the Moon 3. The landing velocity 4. The approach angle 5. The temperature variation

Discuss some of the implications of the differences that the students have listed, for example, the atmosphere. How does the fact that there is no atmosphere on the Moon affect the landing? A parachute would not work on a Moon landing – maybe they need an engine instead or maybe an airbag. Heat shields are a necessity when returning to the Earth due to the friction with the atmosphere, but on the Moon they would not be necessary. Conversely, the temperature variations on the Moon are much more extreme than on Earth, therefore the lander would need to be acclimatised.

2. To solve question 2, students should use the equation for gravitational acceleration (g):

$$g = G\frac{m}{r^2}$$

Where G is the gravitational constant, m is the mass of the planet (moon) and r is the radius of the planet (or moon).

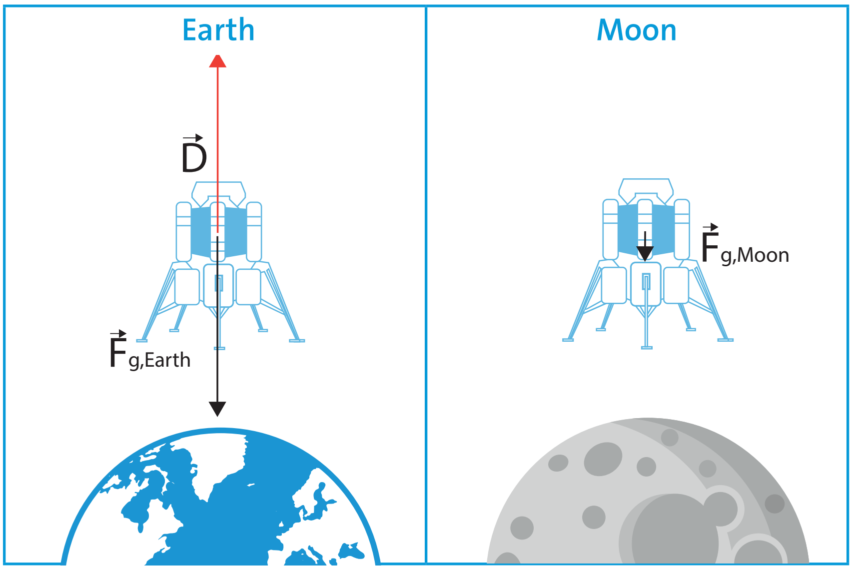
And Newton's Second Law of Motion:

$$F = m * a$$

Where F is the resultant force acting on an object, m is the mass of the object and a is the acceleration.

EARTH	MOON
$g_{Earth} = \frac{5.97 * 10^{24} kg * 6.67408 * 10^{-11} m^3 kg^{-1} s^{-2}}{(6\,371\,000\ m)^2}$ $g_{Earth} = 9.81 ms^{-2}$	$g_{Moon} = \frac{7.35 * 10^{22} kg * 6.67408 * 10^{-11} m^3 kg^{-1} s^{-2}}{(1\,737\,000\ m)^2}$ $g_{Moon} = 1.62 ms^{-2}$
Assuming the mass of the lander is 250 g: $F_{g,Earth} = 9.81 ms^{-2} * 0.25\ kg$ $F_{g,Earth} = 2.45\ N$	$F_{g,Moon} = 1.62 ms^{-2} * 0.25\ kg$ $F_{g,Moon} = 0.41\ N$

3. Ask the students to draw the force diagram of the lander, on Earth and on the Moon. You can choose to start by saying that the gravitational acceleration on the Moon is 6 times less than on Earth, or you can have the students reflect on their calculated result.



The Moon is surrounded by a vacuum, therefore the only force acting on the lander is the gravitational force ($F_{g,Moon}$) or weight. The weight vector of the lander will be 6 times smaller on the Moon than on the Earth, as calculated in question 2.

The Earth is surrounded by an atmosphere, therefore we have to take into consideration aerodynamic drag. The drag force (D) depends of the square of the velocity of the lander. As velocity increases, the drag force will also increase until it equals the weight. When the drag is equal to weight there is no external force on the object and it will continue falling with a constant velocity (terminal velocity).

4. With the analysis done in the previous questions the students should now be aware of some of the main differences between a Moon lander and an Earth lander. Discuss with the groups if using a parachute would be feasible. Also, discuss the advantages and disadvantages of using an engine to land or an airbag to cushion the landing. Ask the students if they would design their lander differently if they did not have to care for the survival of the egg-naut. Relate this to real space exploration and the differences between a manned and unmanned mission.

→ Conclusion

Students should conclude that landing a lunar lander is a difficult task, which involves many considerations and tests prior to its execution. They should conclude that skills, such as developing a project with a fixed budget, evaluating risk, design, testing, and working as a team, are crucial to any space mission. The considerations that have to be done and the risk involved in manned missions is much higher than for robotic missions.

Students should also conclude that tests performed on Earth cannot fully replicate the environment and conditions of landing on the Moon, therefore, a testing must be supplemented with theory to understand the differences between the Earth and the Moon.

→ LANDING ON THE MOON

Planning and designing a lunar lander

→ Activity 1: Design and build a lunar lander

ESA has tasked you to design a lander that can bring an egg-naut safely to the Moon's surface.

Exercise

Like in the real world space industry, you are competing and/or collaborating with other organisations (your classmates) for a contract with ESA.

Your mission is to:
- Design and build a lunar lander to land an egg-naut safely on the Moon.

Requirements:
- The lander has to pass a drop-test on Earth and the egg-naut must survive the landing.
- You can only use the available materials.
- The lander has to be built within a set budget (a maximum of 1 billion €).
- The lander should be able to land accurately on an appointed landing site.
- You must present a risk assessment and design study.
- You must complete the design and build the lander in the allocated time: 60 minutes.

Did you know?

The total cost of the Apollo space program that took humans to the Moon was $25.4 billion – that is more than $200 billion in today's currency, adjusted for inflation. In 2018, ESA's total budget was 5.6 billion Euros. Currently, space agencies and industry are working together to develop a more sustainable Moon exploration programme. It should be noted that today, we will still use part of the infrastructure created in the 1960s: test chambers, launch pads, mission control centres, ground stations, engineering knowledge, technology, materials and thus a lunar exploration programme will be much more sustainable from the beginning.

Buzz Aldrin at work at the Eagle landing module on the lunar surface. →

Risk Assessment Study

When designing a space mission there are two main factors to consider: risk and cost. For your mission you want to make sure your egg-naut lands safely, but you still want an affordable mission in order to win the contract with ESA.

Place the risks listed on the right in the risk assessment matrix according to their likelihood of happening and the consequences if they do:

		Consequences				
		Insignificant	Minor	Moderate	Major	Catastrophic
Likelihood	Almost certain					
	Likely					
	Possible					
	Unlikely					
	Rare					

1. We do not land at the appointed landing site
2. There are unexpected changes to the requirements
3. The egg-naut does not survive
4. There are unexpected changes to the budget
5. Some materials become unavailable
6. Some materials become too expensive
7. The lander becomes very heavy
8. Another company (group) has an efficient and cheaper design
9. Continuously changing the design means the lander cost too much to build
10. We get delayed
11. The lander is damaged during testing
12. The lander is damaged during transportation
13. The lander is damaged during the final landing

Select three of the major risks and write down how to mitigate them:

1) Risk #: ___________ Mitigation plan: ______________________________

____

2) Risk #: ___________ Mitigation plan: ______________________________

____

3) Risk #: ___________ Mitigation plan: ______________________________

____

Design study

Name of landing module ______________ Name of egg-naut ____________________

Check the materials available and prices with your teacher. Make an accurate sketch of what your landing module will look like. Discuss how the different parts and materials work to protect the egg-naut. Make a budget for your lander, based on the prices of each material and do not forget to include the price of the launch and of the training of the egg-naut:

Material	Price per unit	Amount	Price

Price of lander	
Total mass (egg-naut + lander)	
Price of launch	
Price of training of the egg-naut	
Total price (lander + launch + training)	

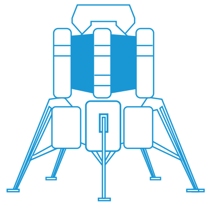
→ Activity 2: Test your landing module

Exercise 1

1. Before the launch, take note of the landing conditions (wind, rain, type of landing site, etc.).

____

____



Make sure your egg-naut is comfortable. Prepare for the test.

Ready! Steady! Drop!!

2. Did the egg-naut survive the drop? **Yes**__________**No**_________

3. How far from the centre of the target did your lander come to rest? ________________ **cm**

4. How well did your design plan work? Would you do something differently now?

____

____

5. After observing the drops of each group, did you notice any recurring design characteristics of the landers in which the egg-naut survived?

____

____

____

____

Exercise 2

For this exercise, you will need to use the displacement of the lander as a function of time.

1. Calculate the impact velocity of the lander using a graph of displacement in the y-direction vs. time

2. Plot velocity in the y-direction as a function of time. Estimate the impact velocity from the plot. Does it correspond to the same value calculated in question 1? Explain the difference, if any.

3. Use the graph of velocity in the y-direction as a function of time to calculate the acceleration of the lander in the y-direction.

4. The gravitational acceleration is 9.8 m/s^2. Explain why you do not retrieve this value.

→ Activity 3: Landing on the Moon

Time to prepare for the landing on the Moon. You have tested your lander on Earth, but what is going to happen when it has to land on the Moon?

1. There are several differences between landing on the Moon and on Earth. List 3 factors that can influence a landing on Earth and on the Moon:

Landing on Earth	Landing on the Moon
1. ____________________	1. ____________________
2. ____________________	2. ____________________
3. ____________________	3. ____________________

2. The gravitational acceleration (g) of a planet is given by:

$$g = G\frac{m}{r^2}$$

Where m is the mass of the planet (or moon), G is the gravitational constant and r is the radius of the planet (or moon). Use the values below to complete questions a) and b):

$G = 6.67408 \times 10^{-11}\ m^3\ kg^{-1}\ s^{-2}$

$r_{Moon} = 1737$ km $\quad m_{Moon} = 7.35 \times 10^{22}$ kg

$r_{Earth} = 6371$ km $\quad m_{Earth} = 5.97 \times 10^{24}$ kg

a) Calculate the gravitational acceleration on the Earth and on the Moon.

$g_{Earth} =$

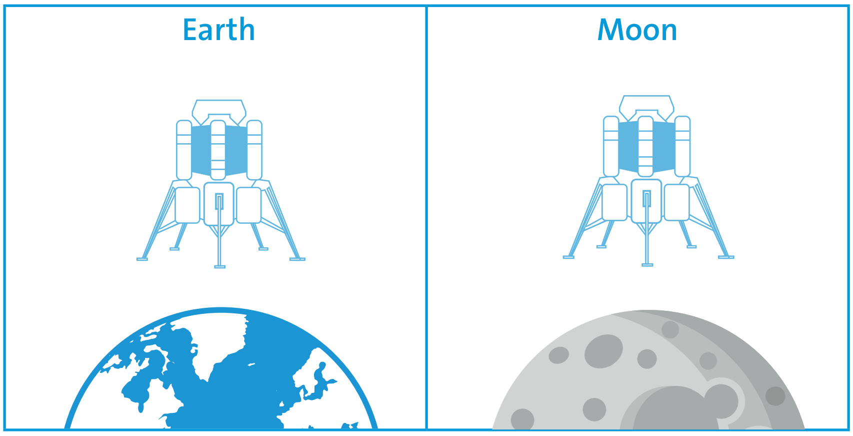
$g_{Moon} =$

b) Using Newton's Second Law of motion $F = m \cdot a$, calculate your lander's gravitational force on Earth and on the Moon.

$F_{g,\ Earth} =$

$F_{g,\ Moon} =$

3. a) Draw the forces acting on the lander, on the Earth and on the Moon.



b) Explain your force diagram.

4. What could you change to make your lander better suited for a Moon landing? Explain.

→ Links

ESA resources

Moon Camp Challenge
esa.int/Education/Moon_Camp

Moon animations about how to get to the Moon.
esa.int/Education/Moon_Camp/Travelling_to_the_Moon

ESA classroom resources:
esa.int/Education/Classroom_resources

ESA space projects

SMART-1
http://sci.esa.int/smart-1

HERACLES
esa.int/Our_Activities/Human_Spaceflight/Exploration/Landing_on_the_Moon_and_returning_home_Heracles

Extra information

ESA's Moon interactive guide
http://lunarexploration.esa.int/#/intro

How to use the Tracker program

Tutorial 1
youtube.com/watch?v=JhI-_glsE6o

Tutorial 2
youtube.com/watch?v=ibY1ASDOD8Y

→ ANNEX 1

Activity 1 - Design and build a lunar lander

Mandatory costs:

Training of egg-naut	300 million €
The cost of the launch	1 million € per gram

Materials:

1 piece of A4 Paper	50 million €
1 straw	100 million €
1 marshmallow	150 million €
1 popsicle stick	100 million €
1 plastic bag	200 million €
1 m of string	100 million €
1 m of tape	200 million €
1 balloon	200 million €

→ ANNEX 2

Activity 2 - Test your landing module

Lander name	Drop height (m)	Distance from target (cm)	Cost (million €)

→ ANNEX 3

Activity 2 - Test your landing module

This part of Exercise 2 can be performed either as a demonstration or as a continuation of the student group activities, depending on the availability of computers or smartphones in your classroom.

Video motion analysis will be used to track the landing. There are several video analysis programs available online - some are free and others require a license. We suggest the use of:

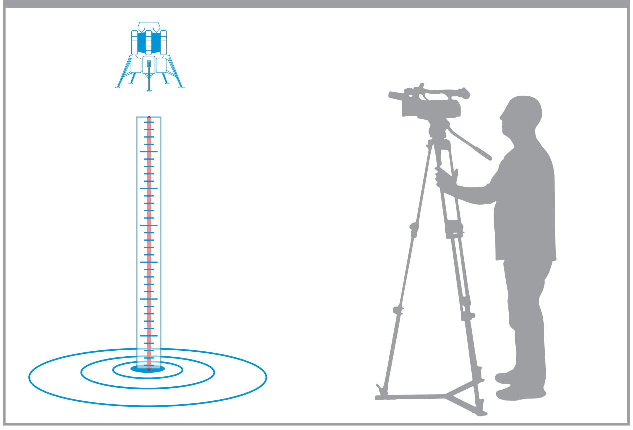
- The "*Tracker program*" is free to download from the http://physlets.org/tracker/ and is well suited for use on a computer.
- The app 'Video Physics' in combination with "Graphical" (both available for Android and iOS) are ideal for tracking with tablets or smartphones.

You can perform the experiment and distribute a single set of data to the students, or they can perform the measurements for their landers individually.

Setup

1. Fasten a meter stick (or a ruler) as a reference next to the landing site.
2. Position the camera in such a way that the drop site and meter stick are in the same frame.
3. Keep the camera steady while filming, ideally using a tripod.
4. When dropping the lander, make sure it is at the same distance as the meter stick from the camera.

Figure A5



↑ Representation of the test drop setting.

Figure A6

↑ Example of a test drop video motion analysis from approximately 2 m height.

5. Track the lander in your selected program by setting marker points manually.
6. Save the data.

Sample data for the lander drop.

Time (s)	Y Displacement (m)	Y Velocity (m/s)
0.000	1.84	-0.406
0.067	1.82	-0.547
0.100	1.79	-0.843
0.133	1.76	-1.148
0.167	1.71	-1.453
0.200	1.66	-1.748
0.233	1.60	-2.096
0.267	1.52	-2.420
0.300	1.44	-2.725
0.333	1.34	-3.006
0.367	1.24	-3.274
0.400	1.12	-3.638
0.433	0.99	-3.931
0.467	0.86	-4.123
0.502	0.71	-4.428
0.535	0.51	-4.734
0.568	0.40	-4.877
0.602	0.22	-4.623
0.668	0.00	-0.798
0.702	0.03	0.457
0.735	0.06	0.614
0.768	0.08	0.386
0.802	0.08	0.135
0.835	0.08	0.066
0.868	0.08	0.115
0.902	0.09	0.207
0.935	0.10	0.151
0.968	0.10	-0.019
1.002	0.10	-0.125
1.035	0.09	-0.201
1.068	0.08	-0.294
1.102	0.07	-0.375
1.135	0.06	-0.426