Project 3: Mission to Mars

Stage 1 - Desired Results

Overview

In the third project, students are in the role of **National Aeronautics and Space Administration (NASA) entry, descent, and landing (EDL) engineers** tasked with answering the question *"*How can we successfully land humans on Mars?*"* EDL engineers are responsible for designing the entry, descent, and landing of landers that carry delicate instruments to Mars. Since the 1970s, NASA has worked to land spacecraft on the surface of Mars, succeeding only six times. The ultimate goal is to successfully land humans on Mars, but this significantly increases the mass of landers and cannot be supported by existing EDL systems. Thus, in this project, students work to maximize the amount of mass the lander can carry and still safely land a crew on Mars. Since Mars is so far away and materials are expensive, EDL engineers first prove that their concepts work on paper and then build prototypes to test on Earth. While Earth's atmosphere is not quite like Mars's, these experiments are the only way for EDL engineers to get a sense of how their device works and what they may need to change to successfully land on Mars. To simulate what an EDL engineer does, students design a lander, complete with parachute and airbag, and drop the lander from a height of at least 3 meters. They analyze the terminal velocity and energy conversions with the goal of landing the lander so that the lander and crew (simulated with eggs) survive impact. At the end of the project, students use NASA's customary reporting procedure and prepare a Verification & Validation (V&V) report. V&V reports are essential for progress at NASA because they both document features of successful systems and target the causes of failures. This project gives students agency by allowing them to make multiple decisions. This supports the course Driving Question: "How can we use physics to creatively solve problems and help us understand our world?"

Project Tasks

Task 1: *Building Background Knowledge and Designing Lander:* Students build knowledge about Mars and NASA's previous (successful and unsuccessful) Mars missions.
Task 2: (Entry) *Energy Analysis*: Students explore energy transformation and conservation to understand what happens during entry into the atmosphere.
Task 3: (Descent) *Parachute Design*: Students design and build a parachute for their lander.
Task 4: (Landing) *Airbag Design*: Students design and build an airbag to ensure their crew can land safely on the surface of Mars.
Task 5: *Qualification Testing and Final V&V Report*: Students do a final drop of the lander and report on their findings in a NASA V&V report. They also complete the project exam.

Estimated Project Length: 5–6 weeks

<table>
<tr><td rowspan="4">ESTABLISHED GOALS

Advanced Placement (AP) Essential Knowledge Statements

1.C.2: Gravitational mass is the property of an object or a system that determines the strength of the gravitational</td><td colspan="2">Transfer</td></tr>
<tr><td colspan="2">Students will be able to independently use their learning to…
● Explain how force, impulse, and change in momentum are all related
● Apply the law of conservation of energy
● Apply physics knowledge and scientific skills in the context of a real-world problem
● Articulate, in writing, their understanding of physics and the role of learning from failure in physics</td></tr>
<tr><td colspan="2">Meaning</td></tr>
<tr><td>UNDERSTANDINGS</td><td>ESSENTIAL QUESTION</td></tr>
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interaction with other objects, systems, or gravitational fields. **2.B.1:** A gravitational field at the location of an object with mass *m* causes a gravitational force of magnitude *mg* to be exerted on the object in the direction of the field. **2.B.2:** The gravitational field caused by a spherically symmetric object with mass is radial and, outside the object, varies as the inverse square of the radial distance from the center of that object. **3.A.1:** An observer in a particular reference frame can describe the motion of an object using such quantities as position, displacement, distance, velocity, speed, and acceleration. **3.B.1:** If an object of interest interacts with several other objects, the net force is the vector sum of the individual forces. **3.B.2:** Free body diagrams are useful tools for visualizing forces being exerted on a single object and writing the equations that represent a physical situation. **3.C.1:** Gravitational force describes the interaction of one object that has mass with another object that has mass. **3.D.2:** The change in momentum of an object occurs over a time interval. **3.E.1**: The change in the kinetic energy of an object depends on the force exerted on the object and on the displacement of the object during the interval that the force is exerted. **4.A.1:** The linear motion of a system can be described by the displacement, velocity, and acceleration of its center of mass. **4.A.2:** The acceleration is equal to the rate of change of velocity with time, and velocity is equal to the rate of change of position with time.	*Students will understand that…* Students will understand the relationships between an object's' mass, the forces being applied to the object (i.e., air resistance and force due to impact), and the time over which those forces are applied. This includes understanding that more force is needed to bring an object to rest in a short period (Impulse-Momentum Theorem). Students will understand that to make the lander land safely, they should reduce the force due to impact by increasing the impact time. Students should recognize this concept as impulse. Students will understand that mass and velocity are the only two factors that determine an object's kinetic energy. Students will understand that work changes the kinetic energy of an object. To change an object's energy, a force must be applied on the object over a distance (Work-Energy Theorem). Students will understand that the only factors that affect gravitational potential energy are mass and height. Students should also recognize that gravitational potential energy is only present in a system that contains both the lander and planet. Students will understand when the mechanical energy for a system is conserved. Students should recognize that external forces acting on the system changes the total mechanical energy.	How can we successfully land humans on Mars? PREREQUISITE TOPICS ● Forces ● Vectors ● Free-body Diagrams ● Center of mass ● Friction ● One-dimensional kinematics and graphs ● Free-fall motion

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<td rowspan="3">4.A.3: Forces that systems exert on each other are due to interactions between objects in the systems. If the interacting objects are parts of the same system, there will be no change in the center-of-mass velocity of that system.
4.B.1: The change in linear momentum for a constant mass system is the product of the mass of the system and the change in velocity of the center of mass.
4.B.2: The change in linear momentum of the system is given by the product of the average force on that system and the time interval during which the force is exerted.
4.C.1: The energy of a system includes its kinetic energy, potential energy, and microscopic internal energy. Examples should include gravitational potential energy, elastic potential energy and kinetic energy.
4.C.2: Mechanical energy is transferred into or out of a system when an external force is exerted on a system such that a component of the force is parallel to its displacement. The process through which energy is transferred is called work.
5.A.1: A system is an object or collection of objects. The objects are treated as having no internal structure.
5.A.2: For all systems under all circumstances, energy, charge, linear momentum, and angular momentum are conserved. For an isolated or closed system, conserved quantities are constant. An open system is one that exchanges any conserved quantity with its surroundings.
5.A.3: An interaction can be either a force exerted by objects outside the system or the transfer of some quantity with objects outside the system.
5.B.1: Classically, an object can only have kinetic energy since potential energy requires an interaction between two or more objects.</td>
<td>Students will understand the relationship between work and gravitational potential energy (Work-Energy Theorem).

Students will understand the relationship between conservation of energy and forces (Work-Energy Theorem).

Students will understand the relationship between work and the direction of the force as well as other sign conventions of work done on or by the system.

Students will understand the relationship between power and energy.</td>
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<td colspan="2">Acquisition</td>
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<td>Students will know the following:

Students will know that a graph of Velocity vs. Time becomes horizontally linear as it reaches terminal velocity and that the acceleration eventually reaches zero.

Students will know that as the cross-sectional area increases, an object will have a lower terminal velocity.

Students will know that the greater the weight of an object the greater the terminal velocity.

Students will know that the direction of an applied force and the motion of an object are related to any change in energy of the object.

Students will know that power represents the rate of energy change.</td>
<td>Students will gain or utilize the following skills:

Students will be able to plot graphs with data and sketch the general shape of the relationship between two variables in certain situations.

Students will be able to interpret a Velocity vs. Time graph for a falling object that is approaching terminal velocity.

Students will be able to draw free-body diagrams for objects falling in the presence of air resistance. This includes objects in free fall, objects approaching terminal velocity, and objects falling at terminal velocity.

Students will be able to draw free-body diagrams depicting that a greater force of air resistance is required to balance out the greater</td>
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5.B.2: A system with internal structure can have internal energy, and changes in a system's internal structure can result in changes in internal energy. **5.B.3:** A system with internal structure can have potential energy. Potential energy exists within a system if the objects within that system interact with conservative forces. **5.B.4:** The internal energy of a system includes the kinetic energy of the objects that make up the system and potential energy of the configuration of the objects that make up the system. **5.B.5:** An external force exerted on an object or system that moves the object or system through a distance can transfer energy. This process is called doing work on a system. The amount of energy transferred by this mechanical process is called work. Energy transfer in mechanical or electrical systems may occur at different rates. Power is defined as the rate of energy transfer into, out of, or within a system. **AP Science Practices** **1:** The student can use representations and models to communicate scientific phenomena and solve scientific problems. **2:** The student can use mathematics appropriately. **3:** The student can engage in scientific questioning to extend thinking or to guide investigations within the context of the AP course. **3.1** The student can pose scientific questions. **4:** The student can plan and implement data collection strategies in relation to a particular scientific question. **5:** The student can perform data analysis and evaluation of evidence. **6:** The student can work with scientific explanations and theories.	Students will know the definitions of terminal velocity, air resistance, impulse, mechanical energy, kinetic energy, and gravitational potential energy. Students will be able to apply the law of conservation of energy. Students will know that impulse relates to an object's change in velocity and mass (Impulse-Momentum Theorem).	weight of the object in order for that object to reach terminal velocity. Students will be able to calculate the force of gravitational attraction between any two objects. Students will be able to apply the law of conservation of energy in order to look for energy gained or lost by a system. Students will be able to effectively communicate about parachute design, experimental design, and experimental findings. Students will be able to calculate the gravitational potential energy of a system using information from representations of that system. Students will be able to apply the definition of power to solve problems involving energy and time. Students will be able to use evidence from testing their designed landing system to clearly and effectively communicate and analyze successes and failures.

7: The student is able to connect and relate knowledge across various scales, concepts, and representations in and across domains. **7.1** The student can connect phenomena and models across spatial and temporal scales. **7.2** The student can connect concepts in and across domains to generalize or extrapolate in and/or across enduring understandings and/or big ideas.		

Stage 2 - Evidence

Assessment Evidence

PERFORMANCE TASK(S): V&V Report

Throughout the project, students work towards preparing a V&V report. V&V reports are NASA's customary reporting procedure and essential for progress at the agency because they both document features of successful systems and target the causes of failures. The report includes a detailed description and justification of the team's airbag and parachute designs as well as a detailed energy analysis. Teams describe their design rationale and report findings. Should the team experience an unsuccessful landing, they must describe what can be learned from the failure. At NASA, "failures" are just as important as successes in determining the future of the work.

V&V Report Sections (with level 4 descriptors from the rubric)

- TITLE AND ABSTRACT: Includes a descriptive title; summary of the report is clear; includes rationale for why the project and tests were performed; includes important findings.
- INTRODUCTION: Correctly outlines **all** the background information in the context of the project, including terminal velocity, impulse, kinetic energy, and gravitational potential energy. Compares and contrasts the conditions for the class's small-scale testing with an actual Mars EDL.
- ENERGY ANALYSIS: Accurately and quantitatively describes the energy transformations that occur from when the lander is released until landing.
- PARACHUTE DISCUSSION: Includes a clear and complete discussion of the design, scientific justification for design, testing methodology, findings, and recommendations.
- AIRBAG DISCUSSION: Includes a clear and complete discussion of the design, scientific justification for the chosen material, qualitative description of the landing results, and recommendations.
- FINDINGS: Includes a discussion of the success and or failure of the qualification test. This includes calculations for both terminal velocity and maximum change in velocity as well as an explanation of what these values mean.
- CONCLUSION: Contains a restatement of the purpose of this project, a brief restatement of the three main discussions, and a recommendation for future designs and/or testing procedures.

ADDITIONAL SUMMATIVE ASSESSMENT(S): Final project exam

Students demonstrate understanding of physics concepts by answering AP multiple choice and free response questions. Students are assessed on the following:

- Air resistance
- Motion graphs

- Free body diagrams
- Work
- Kinetic energy
- Gravitational potential energy
- Conservation of energy
- Impulse
- Terminal velocity
- Momentum
- Newton's Law of Universal Gravitation
- Systems

Evaluative Criteria

- Exam answer key

FORMATIVE ASSESSMENT(S): Teacher Tips and Teacher Checks are embedded in each lesson to support progress toward the Learning Objectives. Note: The most frequent formative assessment opportunities lie within the 10 investigations in the project.

- Explore the connection between work and changes in kinetic energy
- Explore the connection between work and changes in gravitational potential energy
- Explore Newton's Law of Universal Gravitation
- Understand conservation of energy and its relationship to the "system"
- Be careful with units
- Distinguish between work, power, and energy
- Generate free-body diagrams to depict air resistance
- Determine the factors affecting terminal velocity
- Determine the relationship between impulse and change in velocity
- Gather and analyze evidence from testing
- Articulate written communication of design thinking and analysis of testing

Evaluative Criteria:

- Sample project logs that model accurate student work
- Teacher Checks that contain guidance for teachers to understand (1) where students often struggle, (2) how to help students develop their conceptual understanding, and (3) what to look for in a given activity.

In addition, pre-/post-investigation elicitation questions are often utilized to surface students' existing ideas about core concepts and then, after the investigation, to refine those ideas.

Stage 3 – Learning Plan

Task 1: Building Background Knowledge and Designing Lander

In Task 1, students build background knowledge to take on the role of EDL engineers, tackling the challenge of helping NASA safely land humans on Mars. They design and test a model of a landing system that can land a crew safely.

Lesson 1: **Building Background Knowledge**
Working in groups of four, students do a “Building Background Knowledge” workshop. They learn about Mars, traveling to Mars, and past successful and unsuccessful missions to Mars. The lesson involves use of images, videos, and texts. Not all students are exposed to the exact same set of resources so that they collaborate to build everyone’s understanding.

Lesson 2: Build Lander
Students get an overview of the project, learn about their role, the project task, and the final V&V report they will need to produce. As a class, they explore the work of EDL engineers and the challenges of landing humans safely on Mars. Then, teams draw on what they just learned to reflect on the constraints in this challenge. They build their landers and will use these in subsequent investigations throughout the project.

Task 2: Energy Analysis
In Task 2, students learn to look at the “entry” phase of their lander into the Martian atmosphere through the lenses of energy transformation and conservation. They study kinetic energy, gravitational potential energy, conservation of energy, and the work-energy theorem. They do a mixture of simulations, thought experiments, and laboratory experiments. They also study the law of gravity and the importance of defining a “system” when solving problems. This is the longest task in the project, consisting of six lessons total.

Lesson 1: Work and Kinetic Energy
Students consider that when the lander descends into the Martian atmosphere, it will have a lot of energy. They explore the general concept of energy and look at how work relates to changes in energy and ultimately to changes in speed or velocity. They use a computer simulation to detail these relationships. In this lesson, students also take a look at how certain words in physics have different (and very specific) meanings as compared with their everyday use.

Lesson 2: Work and Gravitational Potential Energy
Students engage in an investigation in which they derive the formula for gravitational potential energy and develop an understanding of the relationship between gravitational potential energy, height, and mass. They identify the force that causes gravitational potential energy as the force of gravity. This sets them up for the next lesson on Newton’s Law of Universal Gravitation.

Lesson 3: Newton’s Law of Universal Gravitation
Students learn how gravitational force is calculated. The value 9.81 m/s^2 is for objects on Earth; in this lesson students learn how that value was determined and how to calculate the acceleration due to gravity on any planet using the planet's radius and mass.

Lesson 4: Conservation of Energy
Students continue their exploration of energy. They begin by observing a brief online simulation. Then, students conduct an investigation to understand conservation of energy. Students also explore the notion of “open” versus “closed” systems.

Lesson 5: Energy Analysis of Curiosity Landing
Students continue to study work and energy to make calculations and predictions about the lander as it descends through Martian atmosphere to the surface. Students see that the total mechanical energy is constantly decreasing. They think about where the energy goes in each stage of landing.

Lesson 6: Work and Power of the Lander

Students look more closely at the direction of work and how energy is transferred into or out of a system. They also learn how to calculate power by looking at how time plays a role in energy changes.
Task 3: Parachute Design In Task 3, students think about how they can slow down their lander as it descends to the surface of Mars. They explore terminal velocity and air resistance and then use what they learn to design and test parachutes for their lander. At the end of the task, each group drafts the beginning of their final V&V report. NASA engineers use V&V reports to communicate findings as well as test the theory behind their designs.
Lesson 1: **Air Resistance and Terminal Velocity** Students think about how to slow down the lander, modeling the first stages of an EDL human landing on Mars. They conduct an investigation about air resistance and terminal velocity to understand how the parachute will help slow down the lander. The use of free-body diagrams is important in this lesson. **Lesson 2**: **Building an Effective Parachute** Understanding the factors that affect terminal velocity helps students design parachutes that keep their landers safe. In this lesson, students apply what they learned to design, build, and test airbags to protect the lander's crew (eggs). They identify when a falling object reaches terminal velocity from a Velocity vs. Time graph and determine the work done by air resistance using the law of conservation of energy. **Lesson 3: NASA V&V Report** With a focus on communicating what they have learned and how that influenced the design of their parachutes, students preview and practice writing a V&V Report, the type of report that NASA scientists and engineers use to communicate findings of their tests as well as the theory behind their designs. Students preview the rubric and a sample V&V report and then begin writing the Introduction, Energy Analysis, and Parachute Design sections of their V&V report.
Task 4: Airbag Design In Task 4, students consider the function of an airbag in absorbing some of the force when the lander meets the ground. Students explore change in velocity and are introduced to the looped concept of **impulse**—which they will revisit in *Crash Scene Investigation*—to figure out how to design an airbag that will keep their lander's fragile cargo safe during the landing.
Lesson 1: Impulse, Force, and Time Students have figured out how to slow their lander down during the descent. Now they must figure out how to protect the lander and crew upon impact with the ground. To begin, students engage in an elicitation question to surface their ideas about the relationship between force and change in velocity. They then conduct an investigation in which they determine the relationship between force, time, change in velocity, and mass, thereby building an understanding of impulse. Finally, students begin to brainstorm an airbag design using what they learned from the lesson. **Lesson 2: Crumple Zone** Students are now ready to design, build, and test their airbags. They build three bumpers for their lander, graphing and analyzing data for each trial. Students use the shape of the graphs and their calculations to evaluate their airbag designs for optimal survivability. There is an option at the end of this lesson to assign some writing for homework. As in Task 3, Lesson 3, students must communicate what they have learned, writing the Airbag Design portion of their V&V Report. Otherwise, this can wait until after the testing in the next and final task.
Task 5: Qualification Testing and Final V&V Report

In Task 5, students complete final modifications to their lander, parachute(s), and airbag and then test their system with a final drop, gathering data on the time of the descent and the survival of the crew. Students reflect on what they learned from their successes and failures and then finalize their V&V Report.

Lesson 1: Sharing Designs (Optional Lesson)
In this lesson, students share their designs with peers and any other interested people (invited students, teachers, experts, etc.). They invite feedback regarding any “last minute” design changes or additions. At the end of the lesson, they need to be prepared for the Qualification Testing (dropping their landers from a height). They will need to record their final designs on paper either in this lesson or the next.

Lesson 2: Qualification Testing
In this lesson, students test their landers and finalize their V&V reports. They test their landers by adding real eggs and dropping the landers. During the drops, students video record their lander’s descent and then check for “survivors.” After all the landers have been tested, the class compares results. Then students complete their V&V report. An option is provided to have students give peer feedback (protocol is in the Teacher Toolbox) using the rubric and/or a resource about scientific writing.

Lesson 3: Project Exam
To demonstrate students’ understanding of key concepts, they take a project exam, created to mirror the AP exam and contextualized project-based learning questions. In class, students review their exam answers.

Summary of Learning

- Air resistance
- Motion graphs
- Free-body diagrams
- Work
- Kinetic energy
- Gravitational potential energy
- Conservation of energy
- Impulse
- Terminal velocity
- Science report writing
- Cooperative group work
- Practice AP questions

Course Concepts

+ Foundational Concepts: These concepts “carry forward” through the course. Students learn them in one project and then are expected to continue to apply that knowledge and formulas to subsequent relevant projects.

% Looped Concepts: Looped concepts are different from foundational concepts because students learn different facets of the concept in different projects. This means that students do not explore the topic in its entirety but instead learn some aspects in one project and then other aspects in a later project. In this course, it is important that students know the physics content to meet the project challenge. That means it may not be a "good fit" to instruct on all aspects of a concept in a given project. When students return to the concept, the teacher explicitly links what students learned previously to the new context. The second time a concept is encountered, it is expected that students gain a deeper and more nuanced understanding.

@ Discrete Concepts: These concepts only appear in one project. Students learn the entirety of the AP objectives and apply them in the context of one project.

Physics Concepts		**Reel Physics**	**When in Rome**	**Mission to Mars**	**Sticks and Stones**	**Crime Scene Investigation**	**Planet Hunters**	**Art in Motion**
Kinematics	1-D Motion	+	+	+	+	+	+	+
Dynamics	Newton’s Laws		+	+	+	+	+	+
	Descriptions of Motion	+	+	+		+	+	+
	Motion Graphs	+	+	+	+	+	+	+
	Free-Body Diagrams		+	+	+	+	+	+
Linear Momentum	Impulse			%		%		
Energy	Work			+	+	+	+	+
	Kinetic Energy			+	+	+	+	+

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Energy, continued	Conservation of Energy			+	+	+	+	+
	Gravitational Potential Energy			+			+	+