Unit Summary
How was it possible for NASA to intentionally fly into Comet Tempel 1?   In this unit of study, students *use mathematical and computational thinking* to examine the processes governing the workings of the solar system and universe. While doing so they *plan and conduct investigations* and *apply scientific ideas* to make sense of Newton's law of gravitation to describe and predict the gravitational forces between objects. The crosscutting concepts of *scale, proportion, and quantity, and patterns* are called out as organizing concepts for these disciplinary core ideas. Students are expected to demonstrate proficiency in *using mathematical and computational thinking* and to use this practice to demonstrate understanding of core ideas.   This unit is based on HS-ESS1-4, HS-PS2-4, and HS-PS2-2. *[Note: The disciplinary core ideas, science and engineering practices, and crosscutting concepts can be taught in either this course or in a high school physics course. If this unit is included in the Capstone course, it becomes an Earth and Space science course, rather than an environmental science course.]*
Student Learning Objectives
Use mathematical or computational representations to predict the motion of orbiting objects in the solar system. *[Clarification Statement: Emphasis is on Newtonian gravitational laws governing orbital motions, which apply to human-made satellites as well as planets and moons.] [Assessment Boundary: Mathematical representations for the gravitational attraction of bodies and Kepler's Laws of orbital motions should not deal with more than two bodies, nor involve calculus.]* (**HS-ESS1-4**)
(Secondary to HS-ESS1-4) **Use mathematical representations of Newton's Law of Gravitation and Coulomb's Law to describe and predict the gravitational and electrostatic forces between objects.** *[Clarification Statement: Coulomb's Law is not addressed in this unit. Emphasis is on both quantitative and conceptual descriptions of gravitational and electric fields.] [Assessment Boundary: Assessment is limited to systems with two objects.]* (**HS-PS2-4**)
(Secondary to HS-ESS1-4) **Use mathematical representations to support the claim that the total momentum of a system of objects is conserved when there is no net force on the system.** *[Clarification Statement: Emphasis is on the quantitative conservation of momentum in interactions and the qualitative meaning of this principle.] [Assessment Boundary: Assessment is limited to systems of two macroscopic bodies moving in one dimension.]* (**HS-PS2-2**)

Quick Links

Part A: *How was it possible for NASA to intentionally fly into Comet Tempel 1?*	
Concepts	**Formative Assessment**
• Kepler's laws describe common features of the motions of orbiting objects, including their elliptical paths around the sun. Orbits may change due to the gravitational effects from, or collisions with, other objects in the solar system. • Algebraic thinking is used to examine scientific data and predict the effect of a change in one variable on another. (e.g., linear growth vs. exponential growth).	*Students who understand the concepts are able to:* • Use mathematical or computational representations to predict the motion of orbiting objects in the solar system. • Use mathematical and computational representations of Newtonian gravitational laws governing orbital motion that apply to moons and human-made satellites. • Use algebraic thinking to examine scientific data and predict the motion of orbiting objects in the solar system.

What it Looks Like in the Classroom

In this unit of study, students develop an understanding of Kepler's laws, which describe common features of the motions of orbiting objects, including their elliptical paths around the sun. They also learn how orbits may change due to the gravitational effect from, or collisions with, other objects in the solar system. They use algebraic thinking and mathematical and computational representations to examine data and predict the motion of orbiting objects, including moons in our solar system and human-made satellites.

Regarding Kepler's first law, students must have experience in creating scale representations of an ellipse with two foci in order to appreciate that the sun and the center of the solar system's mass are the two foci around which the Earth orbits. Having students actually create ellipses with tacks, cardboard, and string will provide a concrete example of Kepler's first law when calculating the eccentricity of various ellipses ranging in values from 0 to 1. Alternatively, online applets such as the one at Planetary Orbit Simulator may be used to explore the eccentricity of Earth's orbit and those of the other planets in our Solar System. The eccentricity of the Earth's orbit is 0.0167, which is near circular, and even though this value is small it does have implications which are explored within the balance of this unit. Students also use a mathematical model to explain the motion of orbiting objects in the solar system, identifying any important quantities and relationships and using units when appropriate.

Regarding Kepler's second law, students must understand that a line joining a planet and the sun sweeps out equal areas during equal intervals of time. Diagrams could be used to facilitate understanding of this concept. For example, students can use technology such as the Planetary Orbit Simulator to graph an ellipse with an eccentricity of 0.0167. The ellipse can then be divided into equal arc lengths representing time intervals. Next, the area of each wedge can be approximated by finding the area of each approximate triangle. Students should keep accuracy and limitations of measurement in mind while modeling the motion of orbiting objects. Using a pizza that isn't cut symmetrically as an example, ask students where planets are moving fastest and slowest. Ask where areas of greatest centripetal force and acceleration are located.

Students must be able to perform mathematical computations with using Kepler's third law, which states that from the period of a planet's orbit (how long it takes to go around the sun in years), the distance (semi-major axis of the ellipse) of that planet from the sun can be determined.

Kepler's Third Law: $p^2 = a^3$

Kepler observed in the law of harmonies that this ratio is the same for every planet in our solar system. Students should understand the value of one astronomical unit (AU) and the distance from the Earth to the sun (149,597,870.700 kilometers) in order to facilitate calculations for astronomical bodies orbiting our sun. Time can be measured in Earth days or Earth years.

Students must also be able to combine Newton's law of universal gravitation with Kepler's third law to obtain Newton's version of Kepler's third law. This can then be used to describe planetary motion in our solar system with no more than two bodies at a time. Students must be able to predict the motion of human-made satellites as well as planets and moons. Students should be able to describe, for example, why any geosynchronous satellite must always maintain a specific orbit.

Students apply Kepler's and Newton's laws to astronomical data in order to determine the validity of the laws. They might be given astronomical data in the form of numerical tables showing periods and radii. Examples should also include pictorial data of the shapes of orbits of planets in our solar system.

It might be useful to reinforce prior learning of Newton's laws (F=ma, law of inertia) while showing how orbits may change due to the gravitational effects from, or collisions with, other objects in the solar system. Students must be able to explain why planetary orbits may change (e.g., the Kessler Effect, perturbations, wobble, etc.).

Students appreciate how astronomers find extrasolar planets, and explain how observations about an orbiting planet can yield information about the mass and location of the star it orbits.

Students analyze data in which variables such as force, mass, period, and radius of orbit are changed in order to visualize the relationships between a central force and an orbiting body within the context of Kepler's laws as well as the law of universal gravitation. For example, lab data or planetary data may be fed into a computer simulation (PhET), and the resulting orbital behavior analyzed for its compliance with Kepler's laws and universal gravitation.

(Refer to NJ High School Physics Model Curriculum Units 1 and 2 for additional classroom integration ideas for the Physics Performance Expectations integrated into this unit.)

Leveraging Mathematics

Mathematics

- Represent the motion of orbiting objects in the solar system symbolically, and manipulate the representing symbols. Make sense of quantities and relationships about the motion of orbiting objects in the solar system symbolically and manipulate the representing symbols.
- Use a mathematical model to explain the motion of orbiting objects in the solar system. Identify important quantities in the motion of orbiting objects in the solar system and map their relationships using tools. Analyze those relationships mathematically to draw conclusions, reflecting on the results and improving the model if it has not served its purpose.
- Use units as a way to understand the motion of orbiting objects in the solar system and to guide the solution of multistep problems; choose and interpret units representing the motion of orbiting objects in the solar system consistently in formulas; chose and interpret the scale and the origin in graphs and data displays representing the motion of orbiting objects in the solar system.
- Define appropriate quantities for the purpose of descriptive modeling of the motion of orbiting objects in the solar system.
- Choose a level of accuracy appropriate to limitations on measurement when reporting quantities representing the motion of orbiting objects in the solar system.
- Interpret expressions that represent the motion of orbiting objects in the solar system.
- Create equations in two or more variables to represent relationships between quantities representing the motion of orbiting objects in the solar system; graph

equations representing the motion of orbiting objects in the solar system on coordinate axes with labels and scales.

- Rearrange formulas representing the motion of orbiting objects in the solar system to highlight a quantity of interest, using the same reasoning as in solving equations.

Modifications

(Note: Teachers identify the modifications that they will use in the unit. See NGSS Appendix D: All Standards, All Students/Case Studies for vignettes and explanations of the modifications.)

- Structure lessons around questions that are authentic, relate to students' interests, social/family background and knowledge of their community.
- Provide students with multiple choices for how they can represent their understandings (e.g. multisensory techniques-auditory/visual aids; pictures, illustrations, graphs, charts, data tables, multimedia, modeling).
- Provide opportunities for students to connect with people of similar backgrounds (e.g. conversations via digital tool such as SKYPE, experts from the community helping with a project, journal articles, and biographies).
- Provide multiple grouping opportunities for students to share their ideas and to encourage work among various backgrounds and cultures (e.g. multiple representation and multimodal experiences).
- Engage students with a variety of Science and Engineering practices to provide students with multiple entry points and multiple ways to demonstrate their understandings.
- Use project-based science learning to connect science with observable phenomena.
- Structure the learning around explaining or solving a social or community-based issue.
- Provide ELL students with multiple literacy strategies.
- Collaborate with after-school programs or clubs to extend learning opportunities.
- Restructure lesson using UDL principals (http://www.cast.org/our-work/about-udl.html#.VXmoXcfD_UA).

Research on Student Learning

Research suggests teaching the concepts of spherical Earth, space, and gravity in close connection to each other. Students typically do not understand gravity as a force and misconceptions about the causes of gravity persist after traditional high-school physics instruction. These misconceptions about the causes of gravity can be overcome by specially designed instruction. Students of all ages may hold misconceptions about the magnitude of the earth's gravitational force. Even after a physics course, many high-school students believe that gravity increases with height above the earth's surface.

High-school students also have difficulty in conceptualizing gravitational forces as interactions between two objects. In particular, they have difficulty in understanding that the magnitudes of the gravitational forces that two objects of different mass exert on each other are equal therefore resulting in a deeper understanding of the relationships between the object as per of measurable phenomenon. The difficulties persist even after specially designed instruction (NSDL, 2015).

Prior Learning
Physical science • For any pair of interacting objects, the force exerted by the first object on the second object is equal in strength to the force that the second object exerts on the first, but in the opposite direction (Newton's third law). • The motion of an object is determined by the sum of the forces acting on it; if the total force on the object is not zero, its motion will change. The greater the mass of the object, the greater the force needed to achieve the same change in motion. For any given object, a larger force causes a larger change in motion. • All positions of objects and the directions of forces and motions must be described in an arbitrarily chosen reference frame and arbitrarily chosen units of size. In order to share information with other people, these choices must also be shared. • Electric and magnetic (electromagnetic) forces can be attractive or repulsive, and their sizes depend on the magnitudes of the charges, currents, or magnetic strengths involved and on the distances between the interacting objects. • Gravitational forces are always attractive. There is a gravitational force between any two masses, but it is very small except when one or both of the objects have large mass—e.g., Earth and the sun. • Forces that act at a distance (electric, magnetic, and gravitational) can be explained by fields that extend through space and can be mapped by their effect on a test object (a charged object, or a ball, respectively). *Earth and space science* • Patterns of the apparent motion of the sun, the moon, and stars in the sky can be observed, described, predicted, and explained with models. • Earth and its solar system are part of the Milky Way galaxy, which is one of many galaxies in the universe. • The solar system consists of the sun and a collection of objects, including planets, their moons, and asteroids that are held in orbit around the sun by its gravitational pull on them. • This model of the solar system can explain eclipses of the sun and the moon. Earth's spin axis is fixed in direction over the short-term but tilted relative to its orbit around the sun. The seasons are a result of that tilt and are caused by the differential intensity of sunlight on different areas of Earth across the year. • The solar system appears to have formed from a disk of dust and gas, drawn together by gravity.

Connections to Other Courses
Physical science • Newton's second law accurately predicts changes in the motion of macroscopic objects. • Momentum is defined for a particular frame of reference; it is the mass times the velocity of the object. • If a system interacts with objects outside itself, the total momentum of the system can change; however, any such change is balanced by changes in the momentum of objects outside the system.

- Newton's law of universal gravitation provides the mathematical model to describe and predict the effects of gravitational and electrostatic forces between distant objects.
- Forces at a distance are explained by fields (gravitational, electric, and magnetic) permeating space that can transfer energy through space. Magnets or electric currents cause magnetic fields; electric charges or changing magnetic fields cause electric fields.
- Attraction and repulsion between electric charges at the atomic scale explain the structure, properties, and transformations of matter, as well as the contact forces between material objects.

Samples of Open Education Resources for this Unit

(Refer to NJ High School Physics Model Curriculum Units 1, 2, 6 and 8 for additional open education resources for this unit.)

Inverse square law for light and Inverse square law - force: Students use the simulators to ask questions and define problems. Students draw conclusions on inverse relationships based on the data from their activity and support their conclusions with evidence from the activity.

Orbital Motion Students use the simulation to investigate the nature of an elliptical orbit of a planet or other satellite about the Sun or some central body.

Gravity and Orbits: Students analyze the relationship between the Sun, Earth, Moon and space station, including orbits and positions. Students manipulate variables to show how gravity controls the motion of our solar system. Students make predictions how motion would change if gravity was stronger or weaker.

Orbital Motion: Students investigate why planets move in ellipses rather than orbits.

Kepler's Laws of Planetary Motion: Students use a simulation to launch a spacecraft to Mars applying Kepler's Laws.

Students use the simulation to investigate the nature of an elliptical orbit of a planet or other satellite about the Sun or some central body.

Orbit of the Space Station

Mercury's Deviated Orbit

Appendix A: Foundations for the Unit
Use mathematical or computational representations to predict the motion of orbiting objects in the solar system. *[Clarification Statement: Emphasis is on Newtonian gravitational laws governing orbital motions, which apply to human-made satellites as well as planets and moons.] [Assessment Boundary: Mathematical representations for the gravitational attraction of bodies and Kepler's Laws of orbital motions should not deal with more than two bodies, nor involve calculus.]* (**HS-ESS1-4**)
(Secondary to HS-ESS1-4) **Use mathematical representations of Newton's Law of Gravitation and Coulomb's Law to describe and predict the gravitational and electrostatic forces between objects.** *[Clarification Statement: Coulomb's Law is not addressed in this unit. Emphasis is on both quantitative and conceptual descriptions of gravitational and electric fields.] [Assessment Boundary: Assessment is limited to systems with two objects.]* (**HS-PS2-4**)
(Secondary to HS-ESS1-4) **Use mathematical representations to support the claim that the total momentum of a system of objects is conserved when there is no net force on the system.** *[Clarification Statement: Emphasis is on the quantitative conservation of momentum in interactions and the qualitative meaning of this principle.] [Assessment Boundary: Assessment is limited to systems of two macroscopic bodies moving in one dimension.]* (**HS-PS2-2**)

The Student Learning Objectives above were developed using the following elements from the NRC document *A Framework for K-12 Science Education*:

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Using Mathematics and Computational Thinking • Use mathematical representations of phenomena to describe explanations. (HS-ESS1-4), (HS-PS2-2; HS-PS2-4) - ***Connections to Nature of Science*** **Science Models, Laws, Mechanisms, and Theories Explain Natural Phenomena** • Theories and laws provide explanations in science. (HS-PS2-4) • Laws are statements or descriptions of the relationships among observable phenomena. (HS-PS2-4)	**ESS1.B: Earth and the Solar System** • Kepler's laws describe common features of the motions of orbiting objects, including their elliptical paths around the sun. Orbits may change due to the gravitational effects from, or collisions with, other objects in the solar system. (HS-ESS1-4) **PS2.A: Forces and Motion** • Momentum is defined for a particular frame of reference; it is the mass times the velocity of the object. (HS-PS2-2) • If a system interacts with objects outside itself, the total momentum of the system can change; however, any such change is balanced by changes in the momentum of objects outside the system. (HS-PS2-2) **PS2.B: Types of Interactions** • Newton's law of universal gravitation and	**Scale, Proportion, and Quantity** • Algebraic thinking is used to examine scientific data and predict the effect of a change in one variable on another (e.g., linear growth vs. exponential growth). (HS-ESS1-4) **Systems and System Models** • When investigating or describing a system, the boundaries and initial conditions of the system need to be defined. (HS-PS2-2) **Patterns** • Different patterns may be observed at each of the scales at which a system is studied and can provide evidence for causality in explanations of phenomena. (HS-PS2-4)

	Coulomb's law provide the mathematical models to describe and predict the effects of gravitational and electrostatic forces between distant objects. (HS-PS2-4) • Forces at a distance are explained by fields (gravitational, electric, and magnetic) permeating space that can transfer energy through space. Magnets or electric currents cause magnetic fields; electric charges or changing magnetic fields cause electric fields. (HS-PS2-4)	***Connections to Engineering, Technology, and Applications of Science*** **Interdependence of Science, Engineering, and Technology** • Science and engineering complement each other in the cycle known as research and development (R&D). Many R&D projects may involve scientists, engineers, and others with wide ranges of expertise. (HS-ESS1-4)

Embedded English Language Arts/Literacy	Mathematics
N/A	Reason abstractly and quantitatively. (HS-PS2-2), (HS-PS2-4)**,** (HS-ESS1-4) **MP.2** Model with mathematics. (HS-PS2-2), (HS-PS2-4)**,** (HS-ESS1-4) **MP.4** Use units as a way to understand problems and to guide the solution of multi-step problems; choose and interpret units consistently in formulas; choose and interpret the scale and the origin in graphs and data displays. (HS-PS2-2)**,** (HS-PS2-4)**,** (HS-ESS1-4) **HSN.Q.A.1** Define appropriate quantities for the purpose of descriptive modeling. (HS-PS2-2)**,** (HS-PS2-4)**,** (HS-ESS1-4) **HSN.Q.A.2** Choose a level of accuracy appropriate to limitations on measurement when reporting quantities. (HS-PS2-2)**,** (HS-PS2-4)**,** (HS-ESS1-4) **HSN.Q.A.3** Interpret expressions that represent a quantity in terms of its context. (HS-PS2-4), (HS-ESS1-4) **HSA.SSE.A.1** Choose and produce an equivalent form of an expression to reveal and explain properties of the quantity represented by the expression. (HS-PS2-4) **HSA.SSE.B.3** Create equations and inequalities in one variable and use them to solve problems. (HS-PS2-2) **HSA.CED.A.1** Create equations in two or more variables to represent relationships between quantities; graph equations on coordinate axes with labels and scales. (HS-PS2-2) **HSA.CED.A.2** Rearrange formulas to highlight a quantity of interest, using the same reasoning as in solving equations. (HS-PS2-2) **HSA.CED.A.4**