GRAVITY AND SPACE TRAVEL

EDUCATOR GUIDE

INSIDE NASA

FROM DREAM TO DISCOVERY

Museum of Science®

Connections to Education Standards

Next Generation Science Standards:

PERFORMANCE EXPECTATIONS	
MS-PS3-5	Construct, use, and present arguments to support the claim that when the kinetic energy of an object changes, energy is transferred to or from the object.
HS-PS2-4	Use mathematical representations of Newton's Law of Gravitation and Coulomb's Law to describe and predict the gravitational and electrostatic forces between objects.

Massachusetts Science and Technology/Engineering Standards (2013 Draft)

STANDARDS	
4-PS3-3	Ask questions and predict outcomes about the changes in energy that occur when objects collide.
MS-PS1-3	Develop a model that demonstrates Newton's third law involving the motion of two colliding objects.
MS-PS3-2	Develop a model to describe the relationship between the relative position of objects interacting at a distance and their relative potential energy in the system.
MS-PS3-5	Present evidence to support the claim that when the motion energy of an object changes, energy is transferred to or from the object.
HS-PS3-1	Use algebraic expressions and the principle of energy conservation to calculate the change in energy of one component of a system when the change in energy of the other component(s) of the system, as well as the total energy of the system including any energy entering or leaving the system, is known. Identify any transformations from one form of energy to another, including thermal, kinetic, gravitational, magnetic, or electrical energy, in the system.

Massachusetts Science and Technology/Engineering Curriculum Framework (2001)

GRADE LEVEL	SUBJECT	LEARNING STANDARD
3 – 5	**Physical Sciences (Chemistry and Physics)**	5: Give examples of how energy can be transferred from one form to another.
6 – 8	**Physical Sciences (Chemistry and Physics)**	13: Differentiate between potential and kinetic energy. Identify situations where kinetic energy is transformed into potential energy and vice versa.
9 or 10	**Physics**	2.2: Provide examples of how energy can be transformed from kinetic to potential and vice versa.
9 or 10	**Physics**	2.5: Interpret the law of conservation of momentum and provide examples that illustrate it. Calculate the momentum of an object.

Bolded words are defined further in the glossary (page 8).

Introduction

Gravity is an important tool in space flight, especially in the form of planning flight paths for missions. Using a concept called **gravity assist**, the trajectory and speed of a spacecraft can be changed by encountering large bodies, such as planets, in space. Energy and **momentum** are transferred between the planet and the spacecraft, allowing the achievement of velocities and flight path changes that would be impossible otherwise.

To understand this process, it is important to keep in mind the conservations of both energy and momentum.

Conservation and Transfer

The mechanics lie in the conservation of energy and transfer of momentum between the two objects.

First, let's examine the conservation of energy in a planet-spacecraft encounter, designed to speed up the craft, essentially transferring gravitational **potential energy** into **kinetic energy**, and back again.

A reminder of the equations involved:

$$\textit{Gravitational potential energy} = \frac{GMm}{d}$$

Where G is a gravitational constant = $\frac{6.67 \times 10^{-11}\ N \cdot m^2}{kg^2}$, M is the mass of the larger object (in this case, the planet), m is the mass of the spacecraft, and d is the distance between the two objects.

$$\textit{Kinetic energy} = \frac{1}{2} m v^2$$

Where m is the mass of the spacecraft and v is the speed of the spacecraft.

As the spacecraft approaches the planet, some of its kinetic energy is being transferred to gravitational potential energy. Therefore:

$$\frac{1}{2}mv^2 = \frac{GMm}{d}$$

The **mass** of the spacecraft ***(m)*** cancels out on each side of the equations, so this exchange becomes:

$$\frac{1}{2}v^2 = \frac{GM}{d}$$

And because we are most interested in finding a way to change the speed of the spacecraft, we can solve for ***v*** to get:

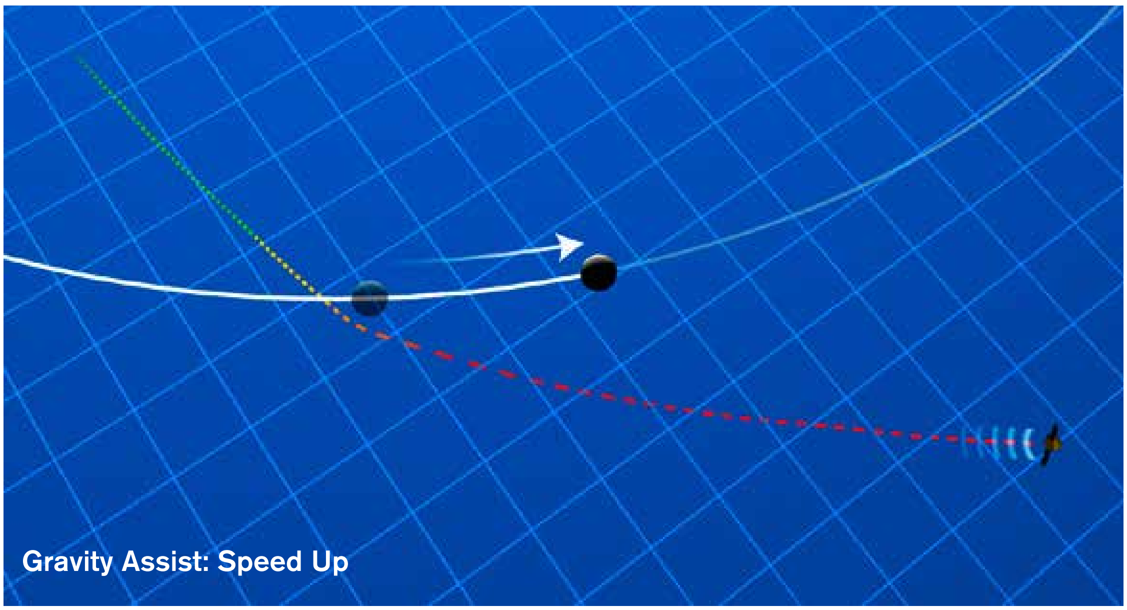
$$v = \sqrt{2\frac{GM}{d}}$$

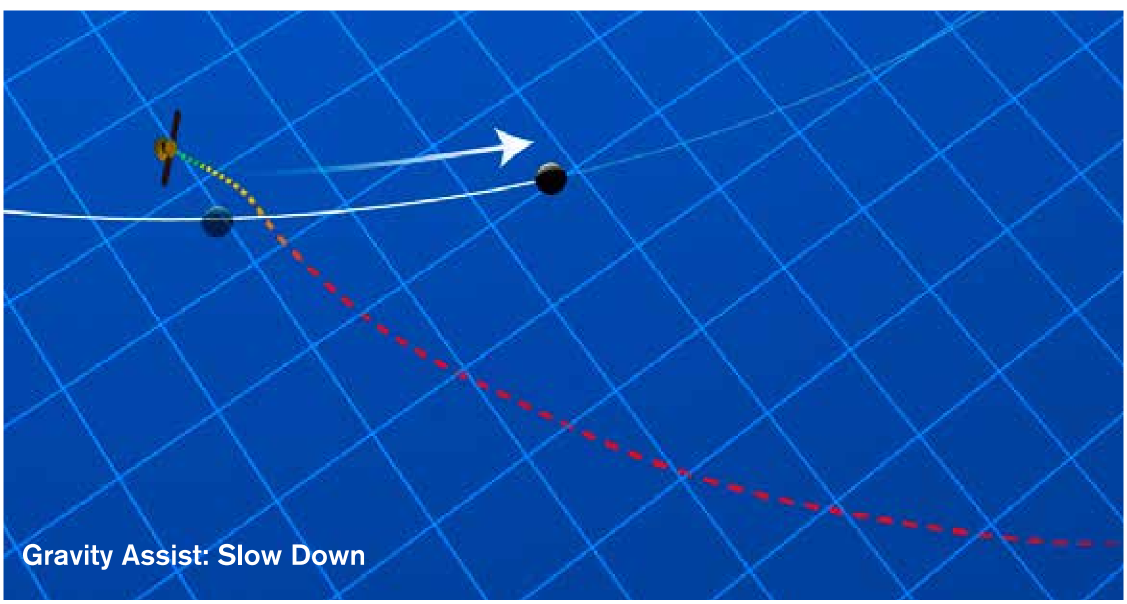
The relationship between gravitational potential and kinetic energy in this particular exchange is such that as the spacecraft gets closer to the planet—leading to a smaller **distance** (***d***)—its speed (***v***) will have to increase. The gravitational pull of the planet causes this interaction, as the spacecraft essentially falls toward the planet.

For energy to be conserved, this also means that as the spacecraft is leaving the planet (leading to a larger distance), its speed will have to decrease again. Assuming a system in which the planet was stationary, this would normally be the result, and there would be no net change in speed. There would, however, be a change of direction. As the spacecraft approaches the planet and experiences increasing gravitational pull, it essentially falls toward the planet and enters the beginnings of an orbit. However, the extra speed gained at closest approach boosts it enough to overcome the pull. This brief tug-of-war "bends" the trajectory of the spacecraft, changing its direction in a predictable way.

To really change the speed of the spacecraft, we need to remember that planets aren't stationary! Since the planet is also moving, it has angular momentum to add to the situation. And because the planet is, essentially, infinitely more massive than the spacecraft, it will be transferring significantly more **velocity** via its momentum during the encounter. This additional velocity boosts the spacecraft's outbound speed quite significantly.

While gravity assists have been discussed so far in the context of accelerating a spacecraft, keep in mind they can also be used as a brake. It all depends on the approach to the planet, and whether the **probe** is stealing some of the planet's momentum to speed up (by coming from behind it) or giving some of its momentum to the planet to slow down (by approaching from in front).





Examples of a spacecraft encountering a planet for a gravity assist. Depending on how the spacecraft approaches the planet, it will either speed up or slow down.

Image: Museum of Science.

What is the Role of Gravity Assist in Space Exploration?

Gravity assists have led to the success of many missions that would be impossible using traditional mechanical means. For example, the *MESSENGER* spacecraft, which reached Mercury in 2011, could not rely on propulsion systems alone to enter **orbit** around the planet. Zipping into the inner solar system, *MESSENGER* would be going much too fast to slow down after a direct approach. So mission planners sent *MESSENGER* on a circuitous route. A year after **launch**, it again passed Earth. From there, it redirected itself to Venus, flying by twice and trading enough momentum with the planet to slow down significantly. Finally, it flew by Mercury three times to slow further, entering orbit almost seven years after it left Earth.

While such roundabout flight paths might seem convoluted, they are necessary. Missions such as Cassini (to Saturn) and Voyagers 1 and 2 (to interstellar space) did not travel directly to their destinations either, instead making several gravity assists along the way. In their cases, they needed boosts to reach high enough speeds to fly farther from the Sun. These speeds would not have been practical with fuel and engine power alone.

And, physics aside, there are economic reasons for gravity assists as well. Not only is spacecraft propellant expensive, but the cost of a bigger rocket to lift more of it into space grows exponentially. Take *MESSENGER*: according to the National Center for Earth and Space Science Education, the probe carried 597 kg (1,316 pounds) of propellant to make course corrections during its flight. The propellant itself cost $48,000, about $300 per gallon. However, the cost of lifting that much weight into orbit was $13 million. So it's in the best interest of the mission planners to save fuel (and weight) by using gravity for free boosts.

Below are some links to external websites with useful information on gravity assists and, in some cases, activities that can be used in the classroom.

Give Me a Boost

messenger-education.org/teachers/Modules/Lessons/MissionDesign_G9-12_L2.pdf
A lesson plan covering two class periods, designed to familiarize students with the physics of gravity assists. *Targeted for grades 9 – 12.*

Gravity Launch

sciencenetlinks.com/tools/gravity-launch
An interactive application that lets you adjust thrust and launch angle to attempt an orbit around the Earth and Moon.

Gravity Assist Simulator

messenger-education.org/Interactives/ANIMATIONS/grav_assist/gravity_assist_menu.html
An interactive application walking through gravity assists in the context of the MESSENGER and New Horizons missions.

Gravity Visualized

youtube.com/watch?v=MTY1Kje0yLg
A teacher-made video demonstrating gravity wells and orbits using materials such as spandex, lead weights, and marbles.

Invisible Force

www-tc.pbskids.org/designsquad/pdf/parentseducators/DSN_NASA_MissionSolarSystem_InvisibleForce.pdf
An activity to design a setup in which, when a steel ball rolls past a magnet, it changes direction and hits an object off to the side. *Targeted for grades 3 – 8.*

NASA Wavelength

nasawavelength.org
NASA Resources for Earth and Space Science Education.

Glossary of Terms

Distance A description of how far apart objects are. In the case of gravity, the distance is measured between the centers of two objects being attracted to each other.

Gravity assist The use of relative movement and the gravity of a large object (typically a planet) to alter the path and speed of a spacecraft.

Kinetic energy (KE) The energy an object has as a result of its motion. It is calculated by the equation: $KE = \frac{1}{2}mv^2$, where "m" is the mass of the object and "v" is the speed of the object in motion.

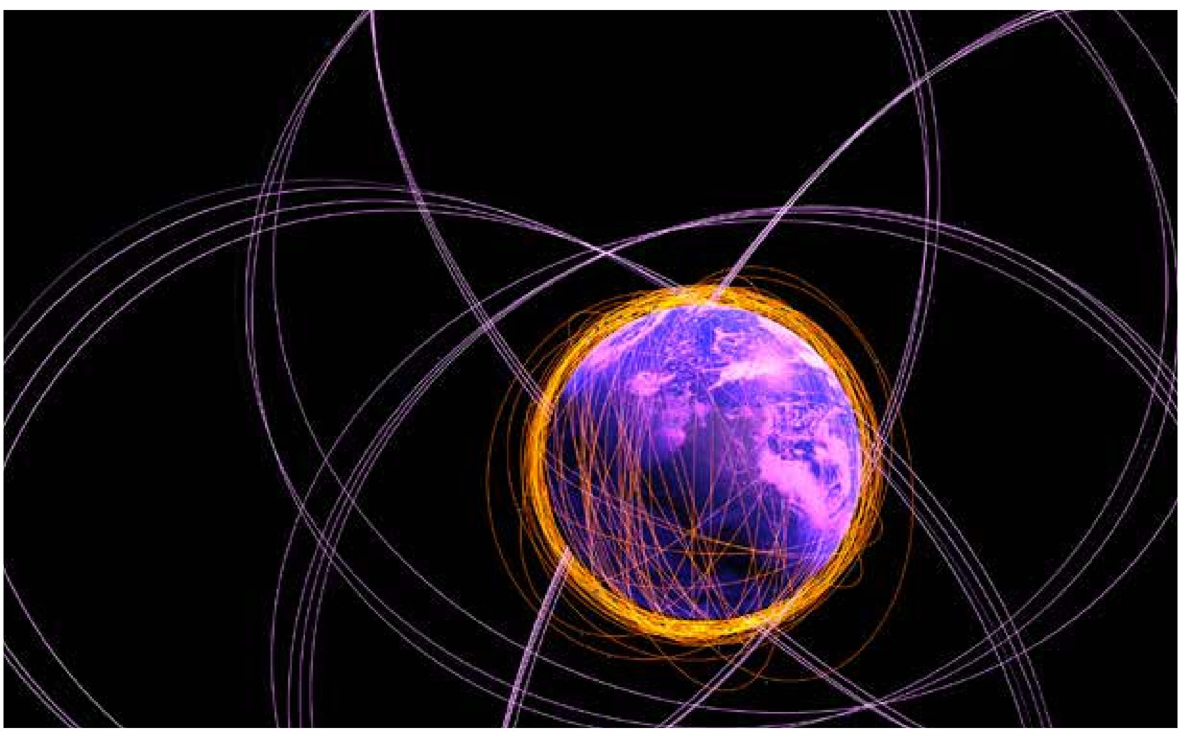
Launch The liftoff of a rocket into space.

Mass The amount of matter contained in an object.

Momentum The product of the mass and velocity of an object (momentum = mass x velocity). An example of an object with a lot of momentum could be a gas giant planet (with a large mass) that is moving quickly (with a lot of velocity) around the Sun.

Motion A movement or change in position with respect to time.

Orbit The curved path of an object around a point in space. The curve of the path is created because the object is moving forward (in a "straight" line) while also being pulled downward by the force of gravity.



Satellites orbiting Earth. *Image: Museum of Science.*

Potential energy (PE) The energy stored in an object due to its position. On Earth, this energy is calculated by the equation: $PE = mgh$, where "m" is the mass of an object, "g" is the acceleration of gravity near the Earth's surface ($9.8\ m/s^2$), and "h" is the height of the object above the surface. In space, it is called "gravitational potential energy (GPE)," and it is calculated by the equation: $GPE = GMm/d$, where "G" is a constant related to the gravitational force between two objects, "M" is the mass of the larger object, "m" is the mass of the smaller object, and "d" is the distance between the two.

Probe An unmanned spacecraft that leaves Earth orbit to explore other objects in space.

Satellite A spacecraft that has been placed in orbit around another object (like the International Space Station, Hubble Space Telescope, etc.)

Thrust In the context of a spacecraft, thrust is a force generated by rocket engines to overcome the weight of the rocket. For example, when rocket fuel is ignited and a gas is accelerated out of the engines, thrust is the force generated in the opposite direction of the accelerating gas. If enough thrust is created, then the rocket will begin to move off the launchpad.

Velocity A description of the rate of change in the position of an object. It must be represented as a speed and a direction (for example: 60 kilometers/hour to the south).

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