Section 5: Conservation of Energy and Gravitation

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5.01
Work

Work – the amount of energy transferred by a force acting over a distance

- Since work represents an amount of energy, it is measured in the SI units for energy, ***joules (J)***. One joule is the same as $1\,\frac{\mathrm{kg \cdot m^2}}{\mathrm{s^2}}$, or $1\ \mathrm{N \cdot m}$.
- Mathematically, W = __________________________.
    - The variable F represents _________________, measured in __________________.
    - The variable d represents _________________, measured in __________________.
    - The symbol θ represents the angle between F and d.

1. You tie a rope around your 2-kg pet turtle's shell and try to take it for a walk, but you soon learn that turtles don't enjoy being walked like dogs. Frustrated, you simply drag the uncooperative turtle behind you through the soft grass. If the rope makes a 30° angle with the flat ground and carries a tension of 5 N, and you drag the turtle 15 m, how much work do you do in this process? How much energy do you deliver to the turtle in this process?

2. What is the minimum amount of work required to lift a 20-kg box from the floor to the top of a shelf that is 1.5 m tall?

5.02
Kinetic and Gravitational Potential Energy

Kinetic energy – energy possessed by any moving object

- All forms of energy can be measured in joules (J).
- Mathematically, $KE =$ ________________________.
    - The variable m represents the mass of the object in kilograms.
    - The variable v represents the speed of the object in meters per second.

Gravitational potential energy – energy possessed by any object lifted above the Earth's surface

- Mathematically, $PE =$ ______________________.
    - The variable m represents the mass of the object, measured in kilograms.
    - The constant g represents the acceleration due to gravity near Earth's surface, also known as the ***gravitational field***. Recall that $g = 9.8\,\frac{\text{m}}{\text{s}^2}$.
    - The variable h represents the height of the object above the ground or other point of reference, measured in meters.

Mechanical energy – the sum of an object's kinetic and potential energies

1. Suppose that 5 seconds after taking off at an angle of 30°, a 1,500-kg airplane is moving at $40\,\frac{\text{m}}{\text{s}}$ at an altitude of 75 m. Calculate its mechanical energy at this point in time.

5.03
Conservation of Energy

Law of conservation of energy – The total energy of any closed system remains constant over time.

- Mathematically, $\Sigma E_i = \Sigma E_f$.
- A closed system is any set of objects that exchange energy only with one another, not with the outside world.
- The entire universe is one example of a closed system.
- Another way of stating the law is "Energy cannot be created or destroyed."

STUDY EDGE TIP

To apply the law of conservation of energy, follow these steps:

1) Make sure you're dealing with a closed system.
2) Write an expression for the total energy of the system in the initial state.
3) Write an expression for the total energy of the system in the final state.
4) Set these expressions equal to one another and solve for the variable you're interested in.

1. Suppose a 100-kg roller coaster cart gliding on a frictionless track goes over the top of a 40-m hill at a speed of 10 $\frac{\mathrm{m}}{\mathrm{s}}$. Continuing on the track, it descends all the way to the ground. Then, it ascends to the top of a 25-m hill. Calculate the cart's speed at the top of this second hill.

2. Suppose a cannonball is fired vertically from the ground at a speed of 35 $\frac{\mathrm{m}}{\mathrm{s}}$. Ignoring air resistance, calculate the maximum height it will reach.

5.04
Elastic Potential Energy

Elastic potential energy – energy stored in a spring or another elastic object when it is stretched or compressed

- Mathematically, $PE_s =$ _________________________.
  - The letter k represents the ***spring constant***, which is a measurement of the stiffness of a spring or an elastic material, measured in $\frac{\text{N}}{\text{m}}$.
  - The variable x represents the distance the spring or material is stretched or compressed from equilibrium, measured in meters.

1. Suppose a pinball machine contains a lightweight spring that launches a 120-g ball at 20 $\frac{\text{m}}{\text{s}}$ when stretched to 8 cm beyond equilibrium and released. Calculate the spring constant of the spring.

5.05
Power

Power – the rate at which energy is expended or transferred

- Power is measured in ***watts (W)***. $1 \text{ W} = 1 \frac{\text{J}}{\text{s}}$.
- Mathematically, P = ________________________.

1. Suppose a hydraulic lift in a garage raises a 2,000-kg car from a height of 2 m to 8 m at a slow, constant speed over a duration of 10 s. What is the power output of the lift?

2. A Bugatti Veryon car has a 1,200-horsepower engine and a mass of 1,900 kg. If 1 horsepower is equal to 746 W, calculate the maximum speed the Bugatti Veryon could theoretically reach from rest in 3 seconds.

5.06
Newton's Law of Gravity

Newton's Law of Gravity – Every object with mass in the universe is attracted to every other object with mass in the universe. The magnitude of this attractive force is directly proportional to each of the two objects' masses and inversely proportional to the square of the radial distance between the objects' centers of mass.

- Mathematically, F_g = ________________________________.
  - The letter G represents the gravitational constant, equal to $6.67 \times 10^{-11} \frac{\text{N}\cdot\text{m}^2}{\text{kg}^2}$.
  - The variables m_1 and m_2 represent the masses of the two attracted objects in kilograms.
  - The variable r represents the distance between the two objects' centers of mass.
- In accordance with Newton's third law, the force of attraction on each of the two objects is equal in magnitude but opposite in direction.

1. Suppose your body has a mass of 50 kg, and a 50-g pencil sits on your desk 30 cm away from you. Calculate the approximate gravitational force of attraction between yourself and the pencil.

2. Suppose you are standing on the surface of Pluto, and you drop a rock. Calculate the acceleration of the rock as it falls, given that the mass of Pluto is 1.31×10^{22} kg, and the planet's radius is 1,187 km.

5.07
Centripetal Motion and Satellites

Centripetal motion – circular motion of an object around a central point

- Any object moving in a circle is constantly changing direction, meaning that its velocity is changing. This means that it is accelerating even though it isn't necessarily changing speed.
- Acceleration that causes circular motion is known as ***centripetal acceleration***.
- Mathematically, $a_c =$ _____________.
- Centripetal acceleration (and the centripetal force that causes it) always points inward, toward the center of the circle.

STUDY EDGE TIP

For objects moving in a circle at constant speed, note the following:

1) The net force on the object represents the centripetal force and always points toward the center of the circle.
2) Apply Newton's second law in the centripetal direction: $\Sigma F_c = ma_c$.
3) To solve for v or r, replace a_c with its formula.

1. Calculate the orbital speed of a satellite in a circular orbit 30,000 km above Earth's surface. The radius of Earth is 6,371 km, and its mass is 5.972×10^{24} kg.