PHYS11 CH9: Work, Energy, and Energy Conservation

From Work to Energy Conservation

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Chapter Sections

9.1 Learning Objectives

By the end of this section, you will be able to:

- Describe and apply the work-energy theorem
- Describe and calculate work and power

9.1 Understanding Work

Work Definition

Work $=$ Force $\times$ Distance (in direction of force)

$$W = F \cdot d$$

Key Points About Work

- Work is done only when force causes displacement
- Force must be parallel to displacement
- Work can be positive or negative:
  - Positive: Force in same direction as motion
  - Negative: Force opposing motion
- No work is done when:
  - Force is perpendicular to motion
  - No displacement occurs

9.1 Work and Force Relationships

Force and Weight

$$F = w = mg$$

Where:

- F = Force (N)
- w = Weight (N)
- m = Mass (kg)
- g = Gravitational acceleration (9.8 $\mathrm{m/s^2}$)

Work and Changes in Gravitational Potential Energy

Work and ΔPE_g Relationship

$$W = \Delta PE_g = mg\Delta h = mg(h_2 - h_1)$$

Where:

- W = Work done (J)
- ΔPE_g = Change in gravitational potential energy (J)
- m = Mass of object (kg)
- g = Gravitational acceleration (9.8 m/s²)
- h_2 = Final height (m)
- h_1 = Initial height (m)
- Δh = Change in height = $h_2 - h_1$ (m)

Important Note

- Positive work ($\Delta h > 0$): Lifting object against gravity
- Negative work ($\Delta h < 0$): Object falling with gravity
- Work done against gravity equals the change in gravitational potential energy of the object

9.1 Work-Energy Theorem

Work-Energy Theorem

$$W = \Delta KE = \frac{1}{2}mv_2^2 - \frac{1}{2}mv_1^2$$

Components

Where:

- W = Net work done on object (J)
- ΔKE = Change in kinetic energy (J)
- m = Mass of object (kg)
- v_1 = Initial velocity (m/s)
- v_2 = Final velocity (m/s)

Key Concept

The net work done on an object equals its change in kinetic energy. This means:

- Positive work increases kinetic energy ($v_2 > v_1$)
- Negative work decreases kinetic energy ($v_2 < v_1$)

9.1 Power - Rate of Work

Power Definition

$$P = \frac{W}{t}$$

Rate at which work is done or energy is transferred

Power Relationships

Alternative forms:

$$P = \frac{W}{t} = \frac{Fd}{t} = F \cdot v$$

$$P = \frac{\Delta E}{t}$$

Where:

- P = Power (watts, W)
- W = Work done (joules, J)
- t = Time interval (seconds, s)
- F = Force (newtons, N)
- v = Velocity (m/s)
- ΔE = Energy change (J)

Real-World Applications

- Engine power ratings

9.1 Example: Calculating Work

Problem: Calculate the work done lifting a 2.0 kg book 1.5 m vertically.

Solution

1. Force needed $=$ weight $=$ mg $= (2.0\ \text{kg})(9.8\ \text{m/s}^2) = 19.6\ \text{N}$
2. Distance $= 1.5$ m
3. Work $= F \times d = 19.6\ \text{N} \times 1.5\ \text{m} = 29.4\ \text{J}$

Units of Work

Work = Force $\times$ Distance

$$W = F \cdot d$$

SI Units

- Force (F): Newtons (N)
- Distance (d): meters (m)
- Work (W): Newton-meters (Nm) = Joules (J)

Unit Analysis

$$1 \text{ Joule} = 1 \text{ N} \cdot 1 \text{ m} = 1 \text{ kg} \cdot \frac{\text{m}}{\text{s}^2} \cdot \text{m} = 1 \text{ kg} \cdot \frac{\text{m}^2}{\text{s}^2}$$

Units of Power

Power = Work ÷ Time

$$P = \frac{W}{t}$$

SI Units

- Work (W): Joules (J)
- Time (t): seconds (s)
- Power (P): Joules per second (J/s) = Watts (W)

Common Power Units

- 1 kilowatt (kW) = 1,000 watts
- 1 horsepower (hp) 746 watts
- 1 kilowatt-hour (kWh) = power $\times$ time = 3,600,000 joules

Units in Energy Equations

Kinetic Energy

$$KE = \frac{1}{2}mv^2$$

Units: $\text{kg} \cdot (\frac{\text{m}}{\text{s}})^2 = \text{kg} \cdot \frac{\text{m}^2}{\text{s}^2} = \text{Joules}$

Gravitational Potential Energy

$$PE = mgh$$

Units: $\text{kg} \cdot \frac{\text{m}}{\text{s}^2} \cdot \text{m} = \text{kg} \cdot \frac{\text{m}^2}{\text{s}^2} = \text{Joules}$

Unit Consistency

All forms of energy (KE, PE, Work) are measured in Joules, allowing direct comparison and conversion between different forms of energy.

phys11-energy-watts-industrial-revolution.png

9.2 Learning Objectives

By the end of this section, you will be able to:

- Explain the law of conservation of energy
- Perform calculations with mechanical energy
- Apply conservation of energy principles

9.2 Types of Mechanical Energy

Kinetic Energy (Energy of Motion)

$$KE = \frac{1}{2}mv^2$$

Gravitational Potential Energy

$$PE = mgh$$

9.2 Conservation of Mechanical Energy

Energy Conservation Equation

$$E_{total} = E_{mechanical} = KE + PE = \text{constant}$$

$$\therefore KE_1 + PE_1 = KE_2 + PE_2$$

What This Means

In a closed system with no friction:

- Initial Energy = Final Energy
- $\frac{1}{2}mv_1^2 + mgh_1 = \frac{1}{2}mv_2^2 + mgh_2$

phys11-energy-conservation-roller-coaster.png

Energy Transformations

State 1	$\rightarrow$	**State 2**
High PE, Low KE (Top of hill)	$\rightarrow$	Low PE, High KE (Bottom of hill)
Low PE, High KE	$\rightarrow$	High PE, Low KE

9.2 Energy Conservation Examples

Example: Roller Coaster

- At top: High PE, Low KE

$$PE_{max} = mgh, \quad KE \approx 0$$

- At bottom: Low PE, High KE

$$PE \approx 0, \quad KE_{max} = \frac{1}{2}mv^2$$

- Total Energy stays constant:

$$mgh = \frac{1}{2}mv^2$$

Key Points

- Energy is never created or destroyed
- Energy only transforms from one form to another
- In real systems, some mechanical energy converts to heat due to friction
- Total system energy always remains constant

9.2 Example: Energy Conservation

A roller coaster car (500 kg) starts from rest at height 40 m. What is its speed at height 15 m?

phys11-energy-conservation-roller-coaster.png

Solution Steps

1. Initial PE $= mgh = (500)(9.8)(40) = 196{,}000$ J
2. Final PE $= mgh = (500)(9.8)(15) = 73{,}500$ J
3. Conservation: PE $=$ PE $+$ KE
4. $196{,}000 = 73{,}500 + \frac{1}{2}(500)v^2$
5. Solve for v

9.3 Learning Objectives

By the end of this section, you will be able to:

- Describe simple and complex machines
- Calculate mechanical advantage and efficiency

9.3 Simple Machines: Basic Mechanical Advantage

General Ideal Mechanical Advantage (IMA)

$$IMA = \frac{F_r}{F_e} = \frac{d_e}{d_r}$$

Where:

- F_r = Resistance force (output force)
- F_e = Effort force (input force)
- d_e = Distance effort moves
- d_r = Distance resistance moves

9.3 Simple Machines: Levers and Wheel-Axle

Lever

$$IMA = \frac{L_e}{L_r}$$

Where:

- L_e = Length of effort arm
- L_r = Length of resistance arm

Wheel and Axle

$$IMA = \frac{R}{r}$$

Where:

- R = Radius of wheel
- r = Radius of axle

phys11-machines-axle-diagram.png

9.3 Simple Machines: Inclined Plane and Wedge

Inclined Plane

$$IMA = \frac{L}{h}$$

Where:

- L = Length of slope
- h = Vertical height

InclinePlane.png

Wedge

$$IMA = \frac{L}{t}$$

Where:

- L = Length of wedge
- t = Thickness of wedge

InclinePlane.png

9.3 Simple Machines: Pulley and Screw

Pulley

$$IMA = N$$

Where:

- N = Number of rope sections supporting the load

Pulley.png

Screw

$$IMA = \frac{2\pi L}{P}$$

Where:

- L = Length of effort arm
- P = Pitch (distance between threads)
- 2π = Circumference factor

phys11-machines-screw-diagram.png

9.3 Work Input and Output

Input Work

$$W_i = F_i d_i$$

Where:

- W_i = Work input (energy put into machine)
- F_i = Input force (effort force)
- d_i = Input distance (distance effort moves)

Output Work

$$W_o = F_o d_o$$

Where:

- W_o = Work output (useful work done by machine)
- F_o = Output force (resistance force)
- d_o = Output distance (distance load moves)

9.3 Machine Efficiency

Efficiency Formula

$$\text{Efficiency} = \frac{W_o}{W_i} \times 100\%$$

Important Points

- Efficiency is always less than 100
- Energy is lost to:
  - Friction between moving parts
  - Heat generation
  - Sound production
- Higher efficiency means less energy waste
- Efficiency can be improved through:
  - Better lubrication
  - Smoother surfaces
  - Proper maintenance

Chapter Summary

- **9.1 Work and Power**
  - Work is force times distance
  - Power is rate of doing work
- **9.2 Energy Conservation**
  - Energy transforms between forms
  - Total energy is conserved
- **9.3 Simple Machines**
  - Machines trade force for distance
  - Efficiency measures useful work output