PHYS11 CH9: Work, Energy, and Energy Conservation

From Work to Energy Conservation

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Chapter Sections

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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

Force and Weight

$$F = w = mg$$

Where:

- F = Force (N)
- w = Weight (N)
- m = Mass (kg)
- g = Gravitational acceleration (9.8 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/s^2)
- 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 $= (2.0 \text{ kg})(9.8 \text{ m/s}^2) = 19.6$ N
2. Distance $= 1.5$ m
3. Work $=$ F $\times$ d $= 19.6 \text{ N} \times 1.5 \text{ m} = 29.4$ J

Units of Work

Work = Force × 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 × 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.

WATCH PHYSICS

Watt's Role in the Industrial Revolution

This video demonstrates how the watts that resulted from Watt's inventions helped make the industrial revolution possible and allowed England to enter a new historical era.

Click to view content (https://www.youtube.com/embed/zhL5DCizj5c)

GRASP CHECK

Which form of mechanical energy does the steam engine generate?

a. Potential energy
b. Kinetic energy
c. Nuclear energy
d. Solar energy

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

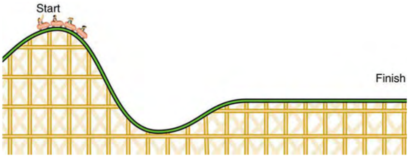

Figure 9.6 During this roller coaster ride, there are conversions between potential and kinetic energy.

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 (Bottom of hill)	$\rightarrow$	High PE, Low KE (Top of hill)

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

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

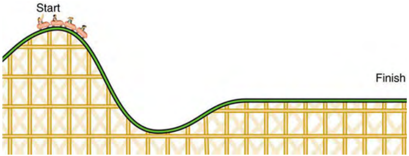

Figure 9.6 During this roller coaster ride, there are conversions between potential and kinetic energy.

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

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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

Lever

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

Where:

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

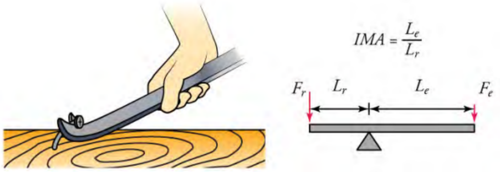

Figure 9.7 (a) A pry bar is a type of lever. (b) The ideal mechanical advantage equals the length of the effort arm divided by the length of the resistance arm of a lever.

Wheel and Axle

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

Where:

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

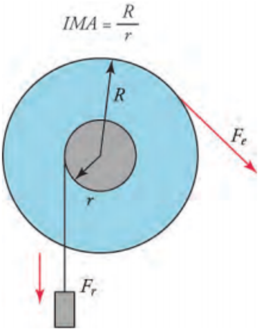

Figure 9.8 Force applied to a wheel exerts a force on its axle.

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

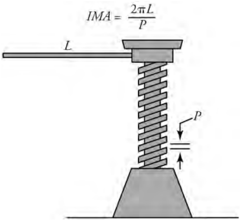

Figure 9.10 The screw shown here is used to lift very heavy objects, like the corner of a car or a house a short distance.

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