Chapter 7

Energy

and

Energy Transfer

Introduction to Energy

- The concept of energy is one of the most important topics in science
- Every physical process that occurs in the Universe involves energy and energy transfers or transformations
- Energy is not easily defined

Energy Approach to Problems

- The energy approach to describing motion is particularly useful when the force is not constant
- An approach will involve *Conservation of Energy*
  - This could be extended to biological organisms, technological systems and engineering situations

Systems

- A *system* is a small portion of the Universe
  - We will ignore the details of the rest of the Universe
- A critical skill is to identify the system

Valid System

- A valid system may
  - be a single object or particle
  - be a collection of objects or particles
  - be a region of space
  - vary in size and shape

Problem Solving

- Does the problem require the system approach?
  - What is the particular system and what is its nature?
- Can the problem be solved by the particle approach?
  - The particle approach is what we have been using to this time

Environment

- There is a *system boundary* around the system
  - The boundary is an imaginary surface
  - It does not necessarily correspond to a physical boundary
- The boundary divides the system from the *environment*
  - The environment is the rest of the Universe

Work

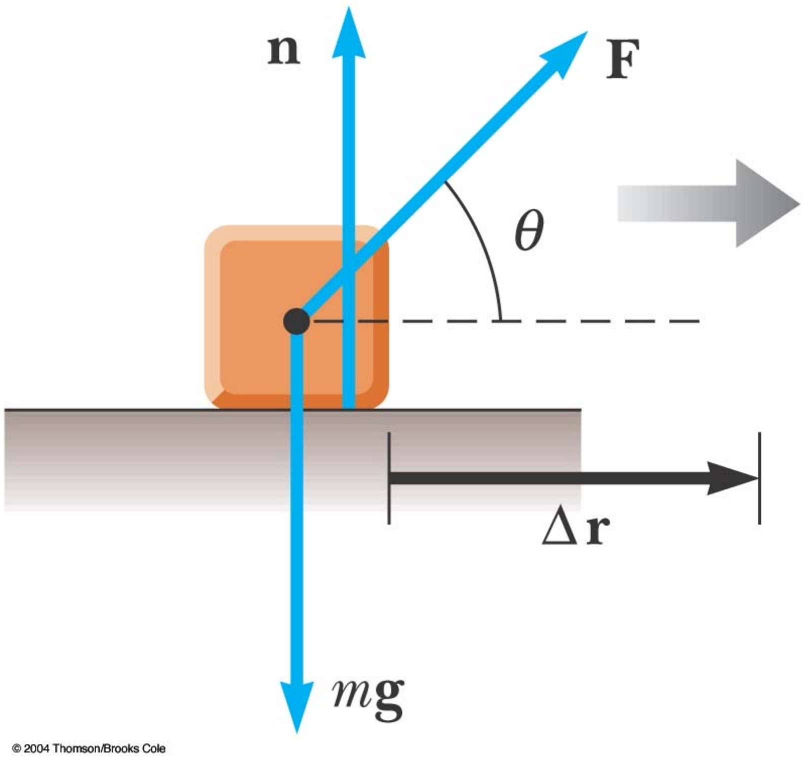
- The work, W, done on a system by an agent exerting a constant force on the system is the product of the magnitude, F, of the force, the magnitude Δr of the displacement of the point of application of the force, and $\cos\theta$, where θ is the angle between the force and the displacement vectors

Work, cont.

- $W = F \Delta r \cos \theta$
  - The displacement is that of the point of application of the force
  - A force does no work on the object if the force does not move through a displacement
  - The work done by a force on a moving object is zero when the force applied is perpendicular to the displacement of its point of application

Work Example

- The normal force, n, and the gravitational force, *m* g, do no work on the object
  - cos $\theta = \cos 90° = 0$
- The force **F** does do work on the object



More About Work

- The system and the environment must be determined when dealing with work
  - The environment does work on the system
    - Work **by** the environment **on** the system
- The sign of the work depends on the direction of **F** relative to Δ**r**
  - Work is positive when projection of **F** onto Δ**r** is in the same direction as the displacement
  - Work is negative when the projection is in the opposite direction

Units of Work

- Work is a scalar quantity
- The unit of work is a joule (J)
  - 1 joule = 1 newton · 1 meter
  - J = N · m

Work Is An Energy Transfer

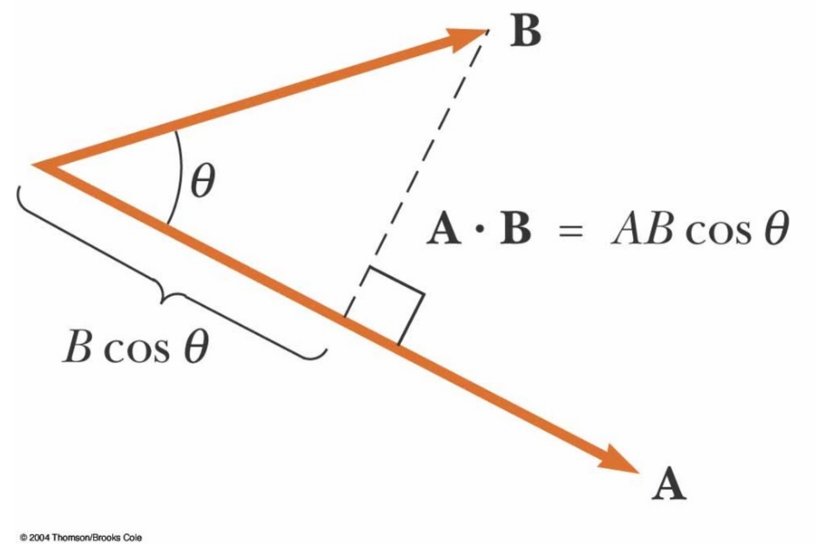
- This is important for a system approach to solving a problem
- If the work is done on a system and it is positive, energy is transferred to the system
- If the work done on the system is negative, energy is transferred from the system

Work Is An Energy Transfer, cont

- If a system interacts with its environment, this interaction can be described as a transfer of energy across the system boundary
  - This will result in a change in the amount of energy stored in the system

Scalar Product of Two Vectors

- The scalar product of two vectors is written as $\mathbf{A} \cdot \mathbf{B}$
  - It is also called the dot product
- $\mathbf{A} \cdot \mathbf{B} = A\,B \cos\,\theta$
  - θ is the angle *between* A and B



Scalar Product, cont

- The scalar product is commutative
  - $\mathbf{A} \cdot \mathbf{B} = \mathbf{B} \cdot \mathbf{A}$
- The scalar product obeys the distributive law of multiplication
- $\mathbf{A} \cdot (\mathbf{B} + \mathbf{C}) = \mathbf{A} \cdot \mathbf{B} + \mathbf{A} \cdot \mathbf{C}$

Dot Products of Unit Vectors

- $\hat{i} \cdot \hat{i} = \hat{j} \cdot \hat{j} = \hat{k} \cdot \hat{k} = 1$

  $\hat{i} \cdot \hat{j} = \hat{i} \cdot \hat{k} = \hat{j} \cdot \hat{k} = 0$

- Using component form with **A** and **B**:

  $A = A_x \hat{i} + A_y \hat{j} + A_z \hat{k}$

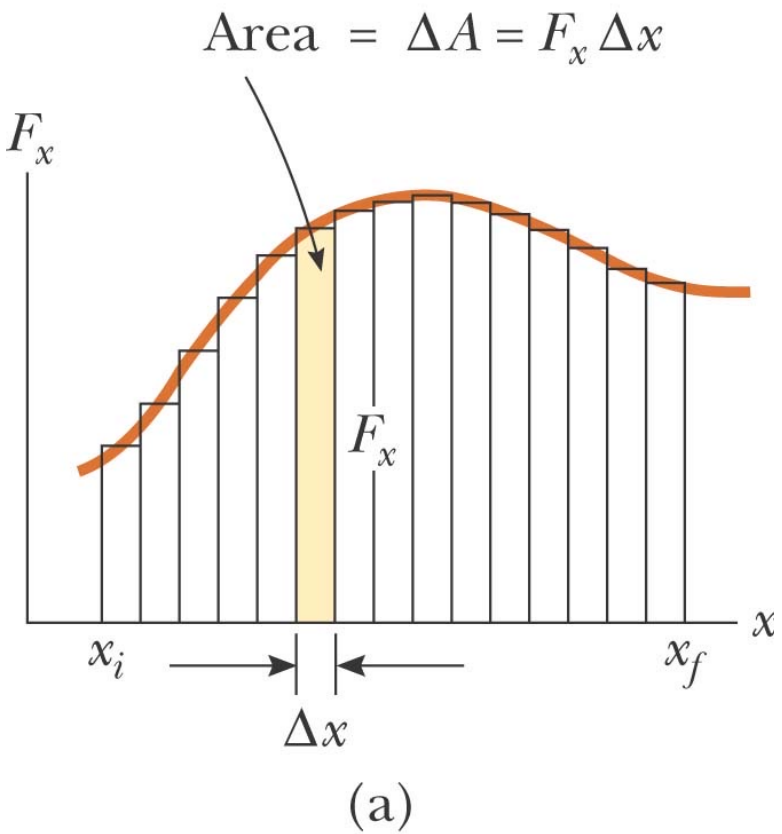
  $B = B_x \hat{i} + B_y \hat{j} + B_z \hat{k}$

  $A \cdot B = A_x B_x + A_y B_y + A_z B_z$

Work Done by a Varying Force

- Assume that during a very small displacement, Δx, F is constant
- For that displacement, $W \sim F \Delta x$
- For all of the intervals,

$$W \approx \sum_{x_i}^{x_f} F_x \Delta x$$



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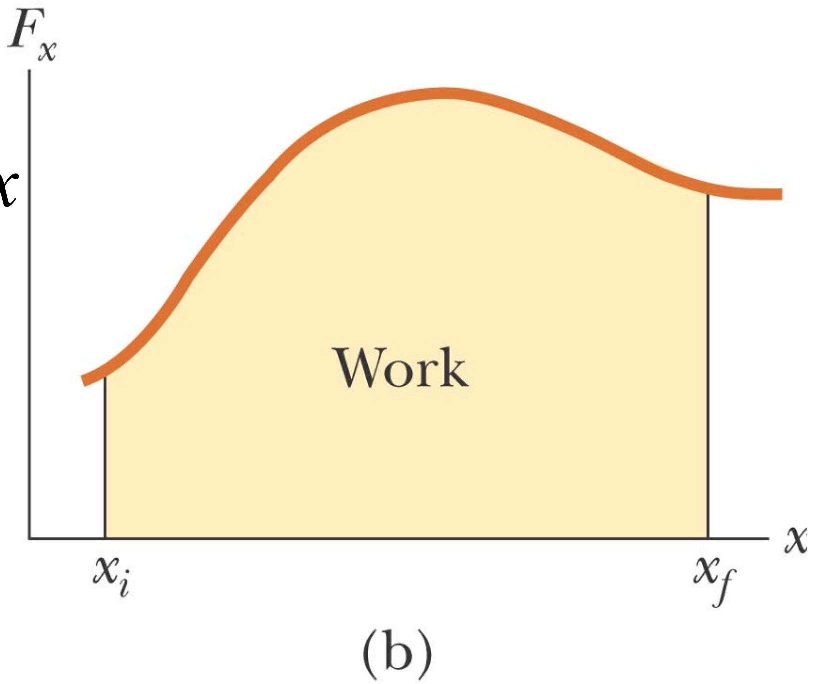
Work Done by a Varying Force, cont

- $$\lim_{\Delta x \to 0} \sum_{x_i}^{x_f} F_x \Delta x = \int_{x_i}^{x_f} F_x dx$$
- Therefore, $W = \int_{x_i}^{x_f} F_x dx$
- The work done is equal to the area under the curve



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Work Done By Multiple Forces

- If more than one force acts on a system and the system can be modeled as a particle, the total work done on the system is the work done by the net force

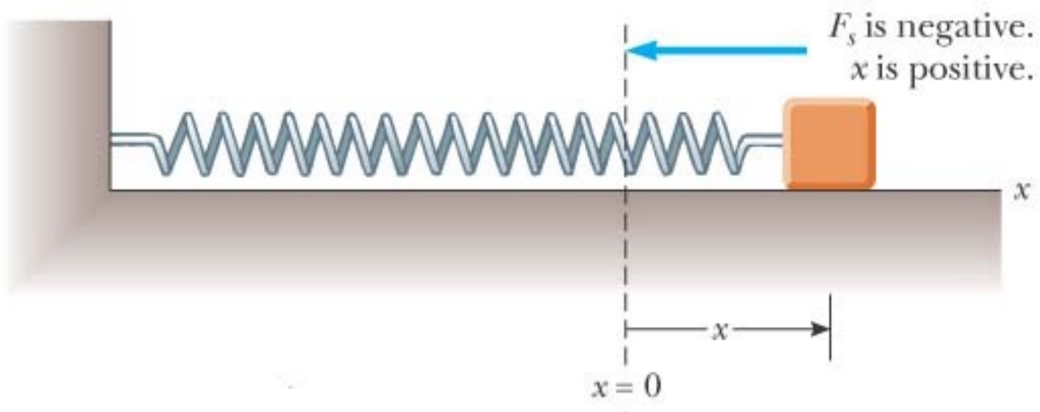
$$\sum W = W_{net} = \int_{x_i}^{x_f} \left(\sum F_x \right) dx$$

Work Done by Multiple Forces, cont.

- If the system cannot be modeled as a particle, then the total work is equal to the algebraic sum of the work done by the individual forces

$$W_{\text{net}} = \sum W_{\text{by individual forces}}$$

Hooke's Law



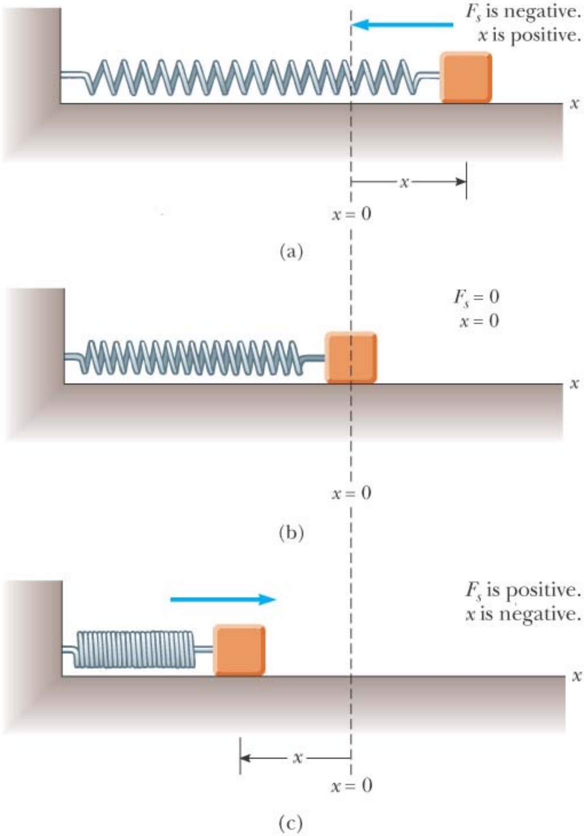
- The force exerted by the spring is

  $$F_s = - kx$$

  - x is the position of the block with respect to the equilibrium position ($x = 0$)
  - k is called the spring constant or force constant and measures the stiffness of the spring
- This is called Hooke's Law

Hooke's Law, cont.

- When *x* is positive (spring is stretched), *F* is negative
- When *x* is 0 (at the equilibrium position), *F* is 0
- When *x* is negative (spring is compressed), *F* is positive



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Hooke's Law, final

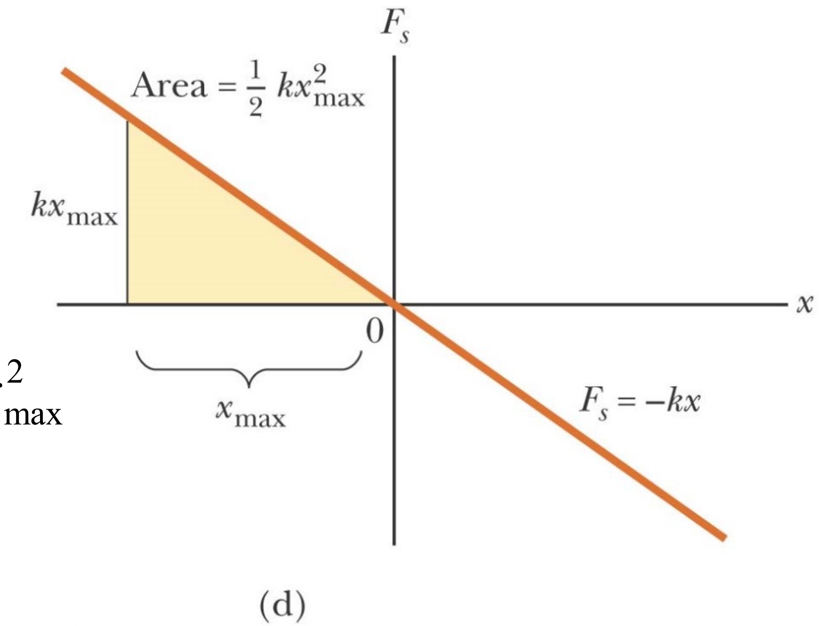
- The force exerted by the spring is always directed opposite to the displacement from equilibrium
- F is called the *restoring force*
- If the block is released it will oscillate back and forth between $-x$ and x

Work Done by a Spring

- Identify the block as the system
- Calculate the work as the block moves from $x_i = -x_{max}$ to $x_f = 0$

$$W_s = \int_{x_i}^{x_f} F_x dx = \int_{-x_{max}}^{0} (-kx)\,dx = \frac{1}{2}kx_{max}^2$$

- The total work done as the block moves from $-x_{max}$ to x_{max} is zero



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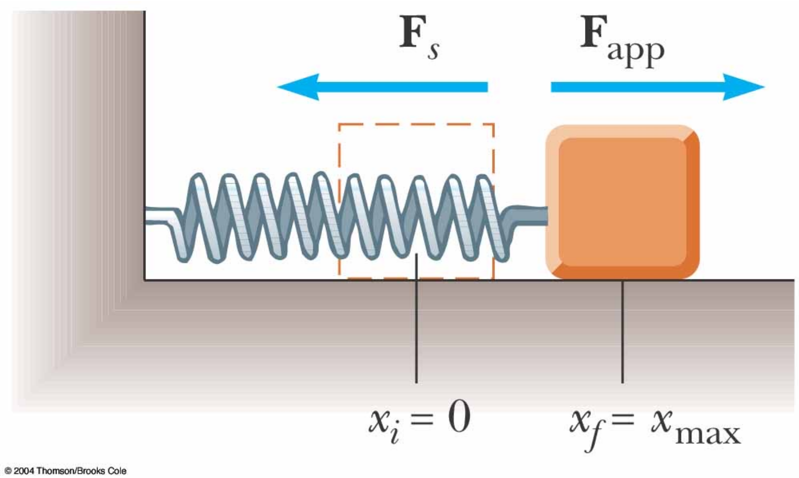
Spring with an Applied Force

- Suppose an external agent, F_{app}, stretches the spring
- The applied force is equal and opposite to the spring force
- $F_{app} = -F_s = -(-kx) = kx$
- Work done by F_{app} is equal to ½ kx^2_{max}



Kinetic Energy

- Kinetic Energy is the energy of a particle due to its motion
  - $K = \frac{1}{2} mv^2$
    - K is the kinetic energy
    - m is the mass of the particle
    - v is the speed of the particle
- A change in kinetic energy is one possible result of doing work to transfer energy into a system

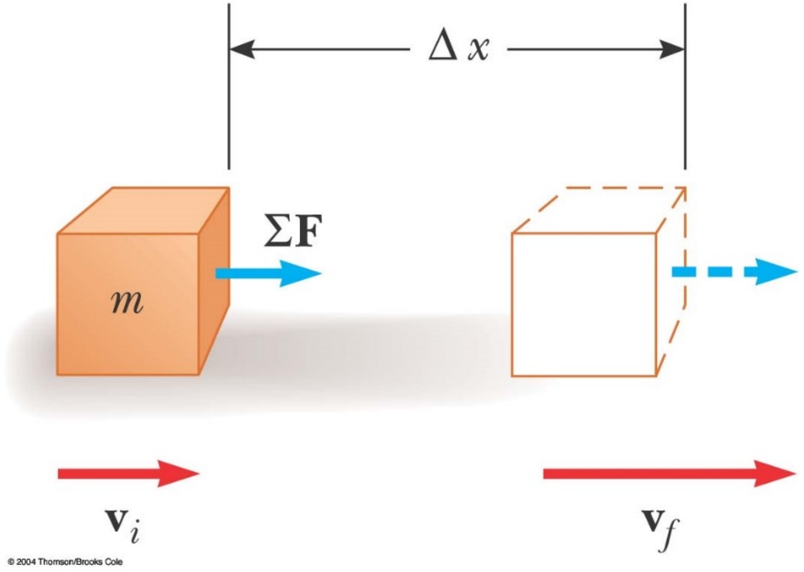
Kinetic Energy, cont

- Calculating the work:

$$W = \int_{x_i}^{x_f} \sum F \, dx = \int_{x_i}^{x_f} ma \, dx$$

$$W = \int_{v_i}^{v_f} mv \, dv$$

$$\sum W = \frac{1}{2}mv_f^2 - \frac{1}{2}mv_i^2$$

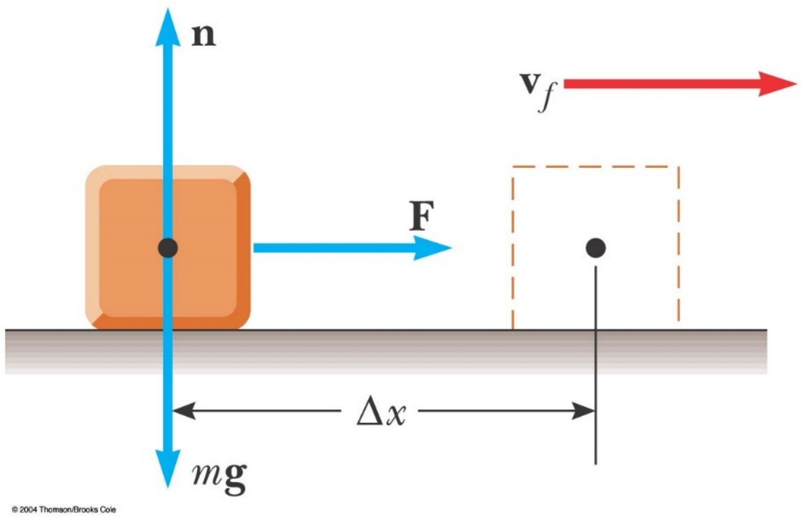


Work-Kinetic Energy Theorem

- The Work-Kinetic Energy Principle states $\Sigma W = K_f - K_i = \Delta K$
- In the case in which work is done on a system and the only change in the system is in its speed, the work done by the net force equals the change in kinetic energy of the system.
- We can also define the kinetic energy
  - $K = \frac{1}{2} mv^2$

Work-Kinetic Energy Theorem – Example

- The normal and gravitational forces do no work since they are perpendicular to the direction of the displacement
- $W = F\Delta x$
- $W = \Delta K = ½\ mv_f^2 - 0$

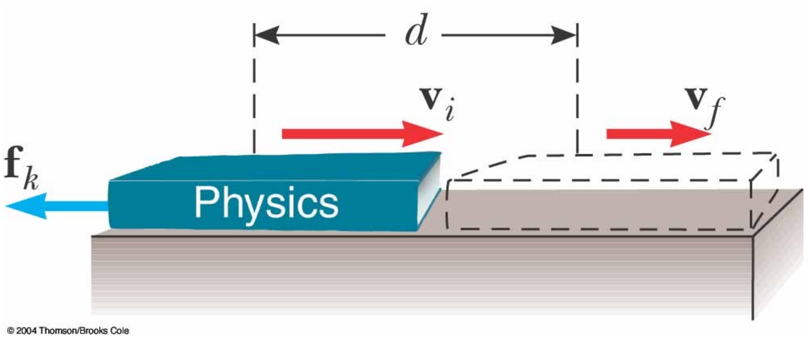


Nonisolated System

- A *nonisolated system* is one that interacts with or is influenced by its environment
  - An *isolated system* would not interact with its environment
- The Work-Kinetic Energy Theorem can be applied to nonisolated systems

Internal Energy

- The energy associated with an object's temperature is called its *internal energy*, E_{int}
- In this example, the surface is the system
- The friction does work and increases the internal energy of the surface



Potential Energy

- *Potential energy* is energy related to the configuration of a system in which the components of the system interact by forces
- Examples include:
  - elastic potential energy – stored in a spring
  - gravitational potential energy
  - electrical potential energy

Ways to Transfer Energy Into or Out of A System

- ***Work*** – transfers by applying a force and causing a displacement of the point of application of the force
- ***Mechanical Waves*** – allow a disturbance to propagate through a medium
- ***Heat*** – is driven by a temperature difference between two regions in space

More Ways to Transfer Energy Into or Out of A System

- ***Matter Transfer*** – matter physically crosses the boundary of the system, carrying energy with it
- ***Electrical Transmission*** – transfer is by electric current
- ***Electromagnetic Radiation*** – energy is transferred by electromagnetic waves

Examples of Ways to Transfer Energy

- a) Work

(a)

- b) Mechanical Waves

(b)

- c) Heat

(c)

Examples of Ways to Transfer Energy, cont.

- d) Matter transfer
- e) Electrical Transmission
- f) Electromagnetic radiation

(d)

(e)

(f)

Conservation of Energy

- ***Energy is conserved***
  - This means that energy cannot be created or destroyed
  - If the total amount of energy in a system changes, it can only be due to the fact that energy has crossed the boundary of the system by some method of energy transfer

Conservation of Energy, cont.

- Mathematically, $\Sigma E_{system} = \Sigma T$
  - E_{system} is the total energy of the system
  - T is the energy transferred across the system boundary
    - Established symbols: $T_{work} = W$ and $T_{heat} = Q$
- The Work-Kinetic Energy theorem is a special case of Conservation of Energy

Power

- The time rate of energy transfer is called ***power***
- The average power is given by

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

when the method of energy transfer is work

Instantaneous Power

- The ***instantaneous power*** is the limiting value of the average power as Δt approaches zero

$$P = \lim_{\Delta t \to 0} \frac{W}{\Delta t} = \frac{dW}{dt}$$

- This can also be written as

$$P = \frac{dW}{dt} = F \cdot \frac{dr}{dt} = F \cdot v$$

Power Generalized

- Power can be related to any type of energy transfer
- In general, power can be expressed as

$$P = \frac{dE}{dt}$$

- *dE*/*dt* is the rate rate at which energy is crossing the boundary of the system for a given transfer mechanism

Units of Power

- The SI unit of power is called the watt
  - 1 watt = 1 joule / second = 1 kg · m^2 / s^2
- A unit of power in the US Customary system is horsepower
  - 1 hp = 746 W
- Units of power can also be used to express units of work or energy
  - 1 kWh = (1000 W)(3600 s) = 3.6 x10^6 J

Energy and the Automobile

- The concepts of energy, power, and friction help to analyze automobile fuel consumption
- About 67% of the energy available from the fuel is lost in the engine
- About 10% is lost due to friction in the transmission, drive shaft, bearings, etc.
  - About 6% goes to internal energy and 4% to operate the fuel and oil pumps and accessories
- This leaves about 13% to actually propel the car

Friction in a Car

- The magnitude of the total friction force is the sum of the rolling friction force and air resistance
  - $f_t = f_r + f_a$
  - At low speeds, rolling friction predominates
  - At high speeds, air drag predominates

Friction in a Car, cont

Table 7.2

Friction Forces and Power Requirements for a Typical Car[a]

v(mi/h)	v(m/s)	n(N)	f_r(N)	f_a(N)	f_t(N)	$\mathcal{P} = f_t v$(kW)
0	0	14 200	227	0	227	0
20	8.9	14 100	226	48	274	2.4
40	17.9	13 900	222	192	414	7.4
60	26.8	13 600	218	431	649	17.4
80	35.8	13 200	211	767	978	35.0
100	44.7	12 600	202	1 199	1 400	62.6

[a] In this table, n is the normal force, f_r is rolling friction, f_a is air friction, f_t is total friction, and $\mathcal{P}$ is the power delivered to the wheels.

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