SUMMARY

GOAL To introduce the concept of energy and to learn a new problem-solving strategy based on conservation of energy.

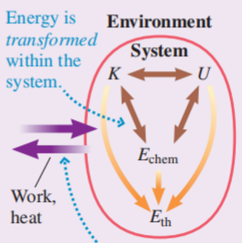
GENERAL PRINCIPLES

Basic Energy Model

Within a system, energy can be **transformed** between various forms.

Energy can be **transferred** into or out of a system in two basic ways:

- **Work:** The transfer of energy by mechanical forces
- **Heat:** The nonmechanical transfer of energy from a hotter to a colder object



Conservation of Energy

When work W is done on a system, the system's total energy changes by the amount of work done. In mathematical form, this is the **work-energy equation:**

$$\Delta E = \Delta K + \Delta U_g + \Delta U_s + \Delta E_{th} + \Delta E_{chem} + \cdots = W$$

A system is isolated when no energy is transferred into or out of the system. This means the work is zero, giving the **law of conservation of energy:**

$$\Delta K + \Delta U_g + \Delta U_s + \Delta E_{th} + \Delta E_{chem} + \cdots = 0$$

Solving Energy Transfer and Energy Conservation Problems

STRATEGIZE Choose the system. Determine the initial and final states.

PREPARE Draw a before-and-after visual overview.

SOLVE Use the before-and-after version of the work-energy equation:

$$K_f + U_f + \Delta E_{th} = K_i + U_i + W$$

Start with this general equation, then specialize to the case at hand:

- Use the appropriate form or forms of potential energy.
- If the system is isolated, set $W = 0$.
- If there is no friction or drag, set $\Delta E_{th} = 0$.

ASSESS See if the numbers make sense—and if the numbers add up. Energy is conserved, and kinetic energy and the change in thermal energy are always positive.

IMPORTANT CONCEPTS

Kinetic energy is an energy of motion:

$$K = \underbrace{\frac{1}{2}mv^2}_{\text{Translational}} + \underbrace{\frac{1}{2}I\omega^2}_{\text{Rotational}}$$

Potential energy is energy stored in a system of interacting objects.

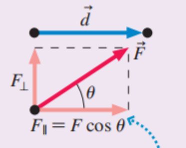
- **Gravitational potential energy:** $U_g = mgy$
- **Elastic potential energy:** $U_s = \frac{1}{2}kx^2$

Thermal energy is the sum of the microscopic kinetic and potential energies of all the molecules in an object. The hotter an object, the more thermal energy it has. When kinetic (sliding) friction is present, the increase in the thermal energy is $\Delta E_{th} = f_k \Delta x$. When the drag force is present, the increase in the thermal energy is $\Delta E_{th} = D\Delta x$.

Work is the process by which energy is transferred to or from a system by the application of mechanical forces.

If a particle moves through a displacement $\vec{d}$ while acted upon by a constant force $\vec{F}$, the force does work

$$W = F_{\parallel}d = Fd\cos\theta$$

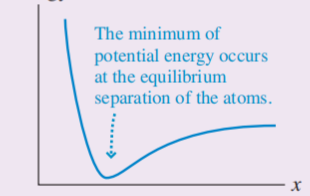


Only the component of the force parallel to the displacement does work.

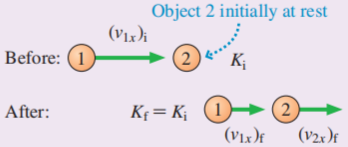
APPLICATIONS

Energy diagrams are a useful way to analyze physical systems.

This curve shows the potential energy of a two-atom molecule as a function of the atomic separation.



Perfectly elastic collisions Both mechanical energy and momentum are conserved.



$$(v_{1x})_f = \frac{m_1 - m_2}{m_1 + m_2}(v_{1x})_i$$

$$(v_{2x})_f = \frac{2m_1}{m_1 + m_2}(v_{1x})_i$$

Power is the rate at which energy is transformed . . .

$$P = \frac{\Delta E \leftarrow \text{Amount of energy transformed}}{\Delta t \leftarrow \text{Time required to transform it}}$$

. . . or at which work is done.

$$P = \frac{W \leftarrow \text{Amount of work done}}{\Delta t \leftarrow \text{Time required to do work}}$$

SUMMARY

GOAL To learn about practical energy transformations and transfers, and the limits on how efficiently energy can be used.

GENERAL PRINCIPLES

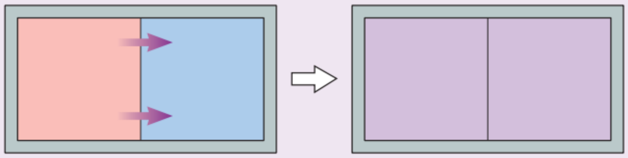
Energy and Efficiency

When energy is transformed from one form into another, some may be "lost," usually to thermal energy, due to practical or theoretical constraints. This limits the efficiency of processes. We define **efficiency** as

$$\underbrace{e}_{\text{Efficiency: Used for heat engines}} = \frac{\text{what you get}}{\text{what you had to pay}} = \underbrace{\text{COP}}_{\text{COP: Used for heat pumps}}$$

Entropy and Irreversibility

Thermal energy tends to spread out. This spreading is irreversible; once the energy has spread, it doesn't go back. This means that heat is transferred from a hot object to a cold object until the two are at equilibrium; once a system is at equilibrium, it will stay there.



The Laws of Thermodynamics

The **first law of thermodynamics** is a statement of conservation of energy for systems in which only thermal energy changes:

$$\Delta E_{th} = W + Q$$

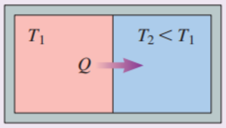
The **second law of thermodynamics** specifies the way that isolated systems can evolve:

The entropy of an isolated system never decreases.

This law has practical consequences:

- Heat energy spontaneously flows only from hot to cold.
- A transformation of energy into thermal energy is irreversible.
- No heat engine can be 100% efficient.

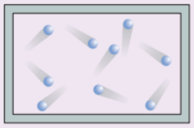
Heat is energy transferred between two objects because they are at different temperatures. Energy will be transferred until thermal equilibrium is reached.



IMPORTANT CONCEPTS

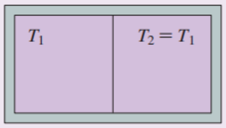
Thermal energy

- For a gas, the thermal energy is the **total kinetic energy** of motion of the atoms.
- Thermal energy is random kinetic energy and so is associated with entropy.



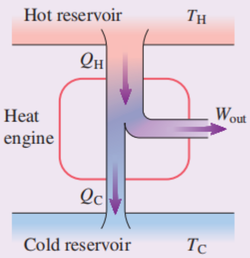
Temperature

- For a gas, temperature is related to the **average kinetic energy** of the motion of the atoms.
- Two systems are in **thermal equilibrium** if they are at the same temperature. No heat energy is transferred.



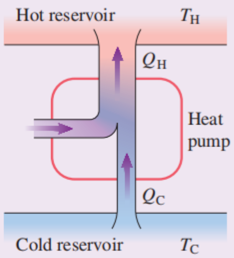
A **heat engine** converts thermal energy from a hot reservoir into useful work. Some heat is exhausted into a cold reservoir, limiting efficiency.

$$e_{max} = 1 - \frac{T_C}{T_H}$$



A **heat pump** uses an energy input to transfer heat from a cold side to a hot side. The **coefficient of performance** is analogous to efficiency. For cooling, its limit is

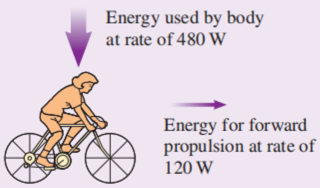
$$\text{COP}_{max} = \frac{T_C}{T_H - T_C}$$



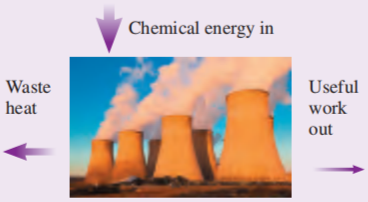
APPLICATIONS

Efficiencies

Energy in the body Cells in the body metabolize chemical energy in food. Efficiency for most actions is about 25%.



Power plants A typical power plant converts about 1/3 of the energy input into useful work. The rest is exhausted as waste heat.



Temperature scales

Zero on the **Kelvin temperature scale** is the temperature at which the kinetic energy of atoms is zero. This is **absolute zero**. The conversion from °C to K is

$$T(\text{K}) = T(°\text{C}) + 273$$

▶ All temperatures in equations must be in kelvin. ◀

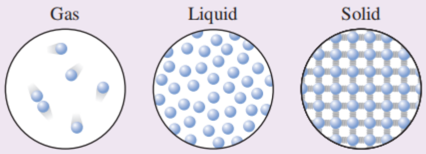
SUMMARY

GOAL To use the atomic model of matter to explain many properties of matter associated with heat and temperature.

GENERAL PRINCIPLES

Atomic Model

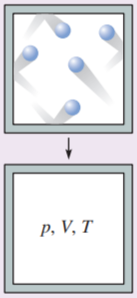
We model matter as being made of simple basic particles. The relationship of these particles to each other defines the phase.



The atomic model explains thermal expansion, specific heat, and heat transfer.

Atomic Model of a Gas

Macroscopic properties of gases can be explained in terms of the atomic model of the gas. The speed of the particles is related to the temperature:



$$v_{\text{rms}} = \sqrt{\frac{3k_BT}{m}}$$

The collisions of particles with each other and with the walls of the container determine the pressure.

Ideal-Gas Law

The ideal-gas law relates the pressure, volume, and temperature in a sample of gas. We can express the law in terms of the number of atoms or the number of moles in the sample:

$$pV = Nk_BT$$
$$pV = nRT$$

For a gas process in a sealed container,

$$\frac{p_iV_i}{T_i} = \frac{p_fV_f}{T_f}$$

IMPORTANT CONCEPTS

Effects of heat transfer

A system that is heated can either change temperature or change phase.

The **specific heat** c of a material is the heat required to raise 1 kg by 1 K. $\quad Q = Mc\,\Delta T$

The **heat of transformation** is the energy necessary to change the phase of 1 kg of a substance. Heat is added to change a solid to a liquid or a liquid to a gas; heat is removed to reverse these changes.

$$Q = \begin{cases} \pm ML_f \text{ (melt/freeze)} \\ \pm ML_v \text{ (boil/condense)} \end{cases}$$

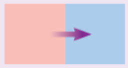
The **molar specific heat** of a gas depends on the process.

$$\begin{cases} \text{For a constant-volume process:} & Q = nC_V\,\Delta T \\ \text{For a constant-pressure process:} & Q = nC_P\,\Delta T \end{cases}$$

Mechanisms of heat transfer

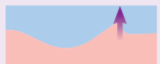
An object can transfer heat to other objects or to its environment:

Conduction is the transfer of heat by direct physical contact.



$$\frac{Q}{\Delta t} = \left(\frac{kA}{L}\right)\Delta T$$

Convection is the transfer of heat by the motion of a fluid.

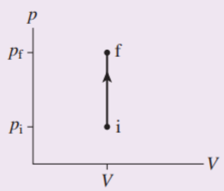


Radiation is the transfer of heat by electromagnetic waves.

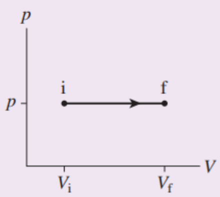
$$\frac{Q}{\Delta t} = e\sigma AT^4$$

A ***pV* (pressure-volume) diagram** is a useful means of looking at a process involving a gas.

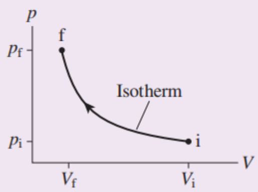
A **constant-volume** process follows a vertical line between initial and final states.



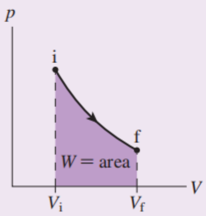
A **constant-pressure** process follows a horizontal line between initial and final states.



A **constant-temperature** process follows a curved path between initial and final states.

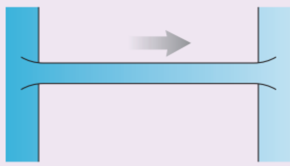


The work done by a gas is the area under the graph.



Diffusion

The random motion of molecules causes diffusion from an area of high concentration to an area of low concentration.



The time for diffusion varies with the square of the distance over which the diffusion occurs:

$$t = \frac{L^2}{6D}$$

APPLICATIONS

Thermal expansion Objects experience an increase in volume and an increase in length when their temperature changes:

$$\Delta V = \beta V_i\,\Delta T \qquad \Delta L = \alpha L_i\,\Delta T$$

Calorimetry When two systems interact thermally, they come to a common final temperature determined by

$$Q_{\text{net}} = Q_1 + Q_2 = 0$$

The number of **moles** is

$$n = \frac{M \text{ (in grams)}}{M_{\text{mol}}}$$

SUMMARY

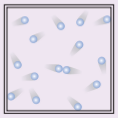
GOAL To understand the static and dynamic properties of fluids.

GENERAL PRINCIPLES

Fluid Statics

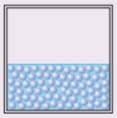
Gases

- Freely moving particles
- Compressible
- Pressure mainly due to particle collisions with walls



Liquids

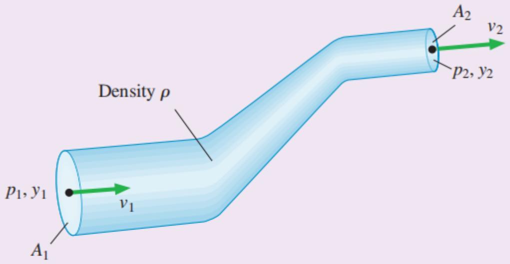
- Loosely bound particles
- Incompressible
- Pressure due to the weight of the liquid



- Hydrostatic pressure at depth d is $p = p_0 + \rho g d$
- The pressure is the same at all points on a horizontal line through a liquid (of one kind) in hydrostatic equilibrium

Fluid Dynamics

We assume that fluids are incompressible, flow is laminar



Equation of continuity

Volume flow rate $Q = \dfrac{\Delta V}{\Delta t}$

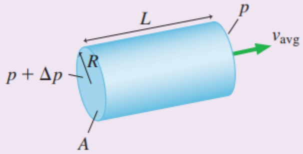
$$= v_1 A_1 = v_2 A_2$$

Bernoulli's equation is a statement of energy conservation:

$$p_1 + \frac{1}{2}\rho {v_1}^2 + \rho g y_1 = p_2 + \frac{1}{2}\rho {v_2}^2 + \rho g y_2$$

Poiseuille's equation governs viscous flow through a tube:

$$Q = v_{avg} A = \frac{\pi R^4 \Delta p}{8 \eta L}$$



IMPORTANT CONCEPTS

Density $\rho = m/V$, where m is mass and V is volume.

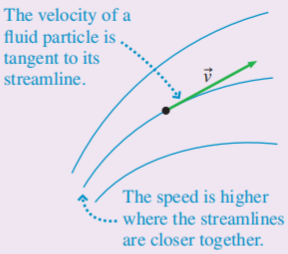
Pressure $p = F/A$, where F is force magnitude and A is the area on which the force acts.

- Pressure exists at all points in a fluid.
- Pressure pushes equally in all directions.
- Gauge pressure $p_g = p - 1$ atm.

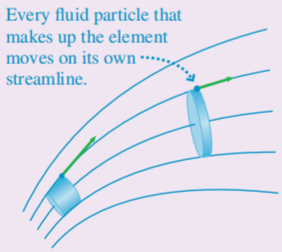
Viscosity η is the property of a fluid that makes it resist flowing.

Representing fluid flow

Streamlines are the paths of individual fluid particles.



Fluid elements contain a fixed volume of fluid. Their shape may change as they move.

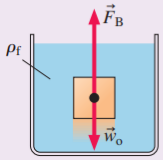


APPLICATIONS

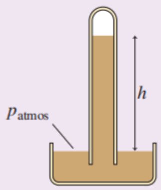
Buoyancy is the upward force of a fluid on an object immersed in the fluid.

Archimedes' principle: The magnitude of the buoyant force equals the weight of the fluid displaced by the object.

Sink:	$\rho_{avg} > \rho_f$	$F_B < w_o$
Float:	$\rho_{avg} < \rho_f$	$F_B > w_o$
Neutrally buoyant:	$\rho_{avg} = \rho_f$	$F_B = w_o$



Barometers measure atmospheric pressure. Atmospheric pressure is related to the height of the liquid column by $p_{atmos} = \rho g h$.



Our understanding of fluids can be applied to the motion of blood in the **circulatory system.**

- The flow is laminar under normal circumstances.
- Blood in the large arteries forms a connected fluid, so height differences matter, but viscosity can be ignored.
- In the small arteries and arterioles, viscosity is a major factor.