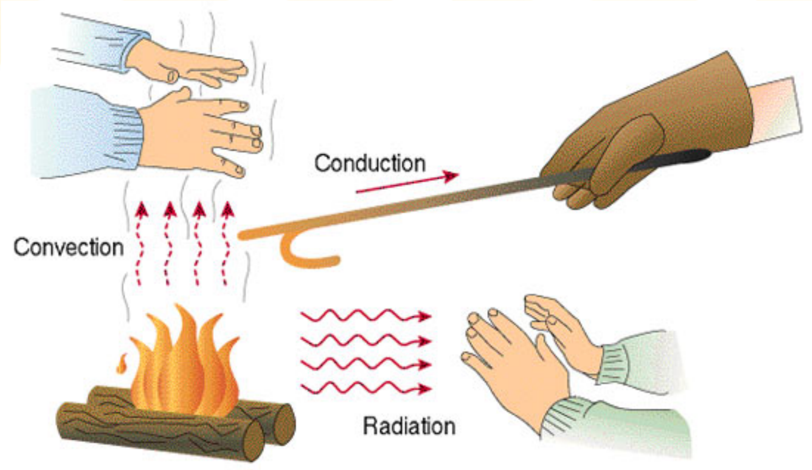
Chapter 11: Energy in Thermal Processes

- Internal Energy and Heat
- Specific Heat
- Latent Heat and Phase Changes
- Energy Transfer

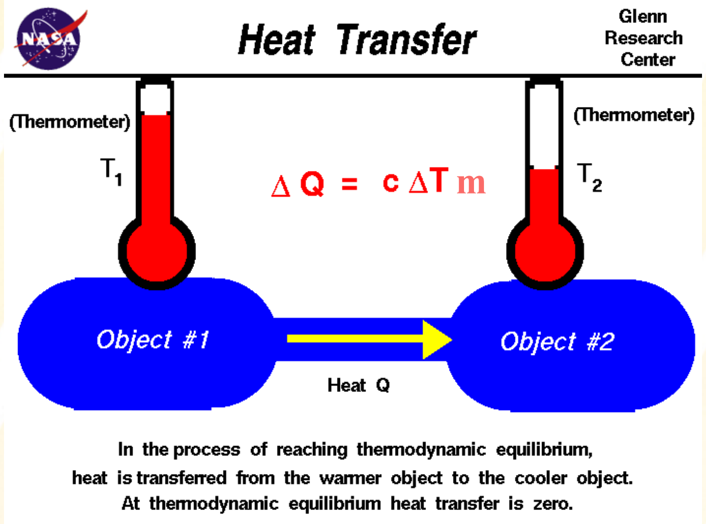


Internal Energy vs. Heat

Internal Energy, U, is the energy associated with the atoms and molecules of the system.

This includes kinetic and potential energy of the atoms/molecules and any bonding energies.

The higher the temperature is, the faster the individual atoms/molecules move and the higher the internal energy is.



Heat, Q, is the energy *transferred* between a system and its environment due to a *temperature difference* between them in order to reach thermal equilibrium (equal temperatures).

$$\boxed{Q = mc\Delta T}$$

Unit: Joule

Here ΔT is the temperature change of a given object due to the heat transfer and c is a material dependent constant called the specific heat. m is the object's mass.

Specific Heat

Specific heat, c, is the energy required to heat 1 kg of a given material up by 1 °C.

$$\boxed{c = \frac{Q}{m\Delta T}}$$

Unit: Joule/(kg · °C)

The specific heat depends on pressure. We will only discuss it at atmospheric pressure.

The specific heat is very different for different materials.

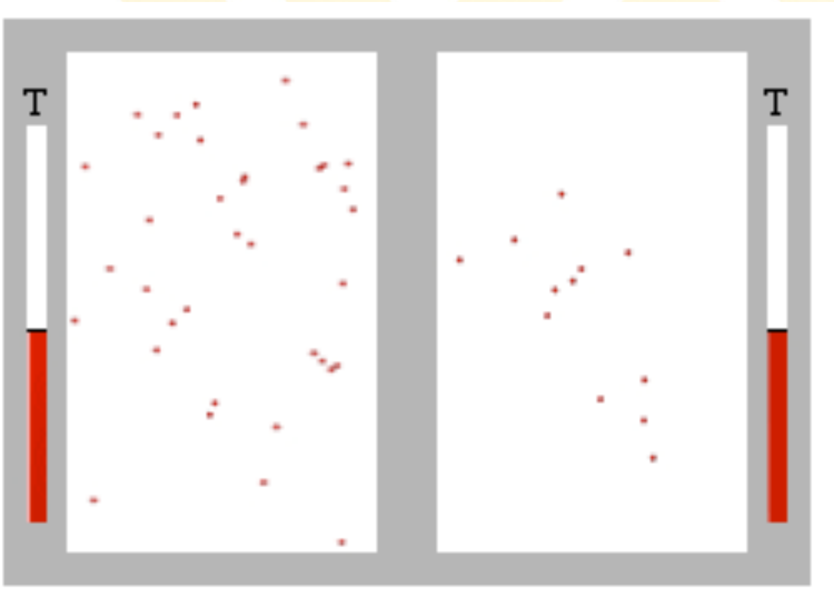
Water has a very high specific heat of 4186 J/(kg °C). This means that water can carry much energy without a big increase of its temperature. Thus, water can used for cooling efficiently.

Table 11.1 Specific Heats of Some Materials at Atmospheric Pressure

Substance	J/kg · °C	cal/g · °C
Aluminum	900	0.215
Beryllium	1 820	0.436
Cadmium	230	0.055
Copper	387	0.092 4
Ethyl Alcohol	2 430	0.581
Germanium	322	0.077
Glass	837	0.200
Gold	129	0.030 8
Human tissue	3 470	0.829
Ice	2 090	0.500
Iron	448	0.107
Lead	128	0.030 5
Mercury	138	0.033
Silicon	703	0.168
Silver	234	0.056
Steam	2 010	0.480
Tin	227	0.054 2
Water	4 186	1.00

Understanding Specific Heat

high c   low c



$$Q = mc\Delta T \qquad \frac{1}{2}mv_{avg}^2 = \frac{3}{2}k_B T$$

Specific heat, c, is the energy required to heat 1 kg of a given material up by 1 °C.

Units of heat

$$Q = mc\Delta T$$

The SI-Unit of heat is Joule.

For historic reasons there is another unit for heat, which is frequently used - the calorie:

1 calorie (cal) is the energy necessary to raise the temperature of 1 g of water from 14.5 °C to 15.5 °C.

We can now calculate how much energy this is:

$$Q = 0.001\,\mathrm{kg} \cdot 4186\,\mathrm{J\,kg^{-1}\,{}^\circ C^{-1}} \cdot 1\,{}^\circ\mathrm{C} = 4.186\,\mathrm{J} \quad \rightarrow \quad \boxed{1\,\mathrm{cal} = 4.186\,\mathrm{J}}$$

The Calorie (Cal) used in describing the energy content of food is actually a kilocalorie.

Example problem: Heat and thermal expansion

A steel strut near a ship's furnace is 2 m long, with a mass of 1.57 kg and cross-sectional area 1 x 10^{-4} m^2. During operation of the furnace, the strut absorbs a net thermal energy of 2.5 · 10^5 J (α_{steel} = 11 · 10^{-6} °C^{-1}, c_{steel} = 448 J/(kg · °C)).

(a) Find the change in temperature of the strut. $$Q = mc\Delta T$$

(b) Find the increase in length of the strut. $$\Delta L = \alpha L_0 \Delta T$$

Latent Heat and Phase Change

Until now we have assumed that a certain transfer of thermal energy (heat) always results in an increase of an object's temperature:

$$Q = mc\Delta T$$

This is, however, only true, if the object does not change its aggregate state of matter, i.e. does not undergo a phase change.

In a phase change, e.g. melting or vaporization, energy is required to break up inter-atomic bonds. This energy cannot be used to increase the temperature.

The total energy required to change the phase of an object of mass m is:

$$\boxed{Q = mL}$$

Unit of L: J/kg

L is called the latent heat (latent = hidden).

Latent heats for different materials

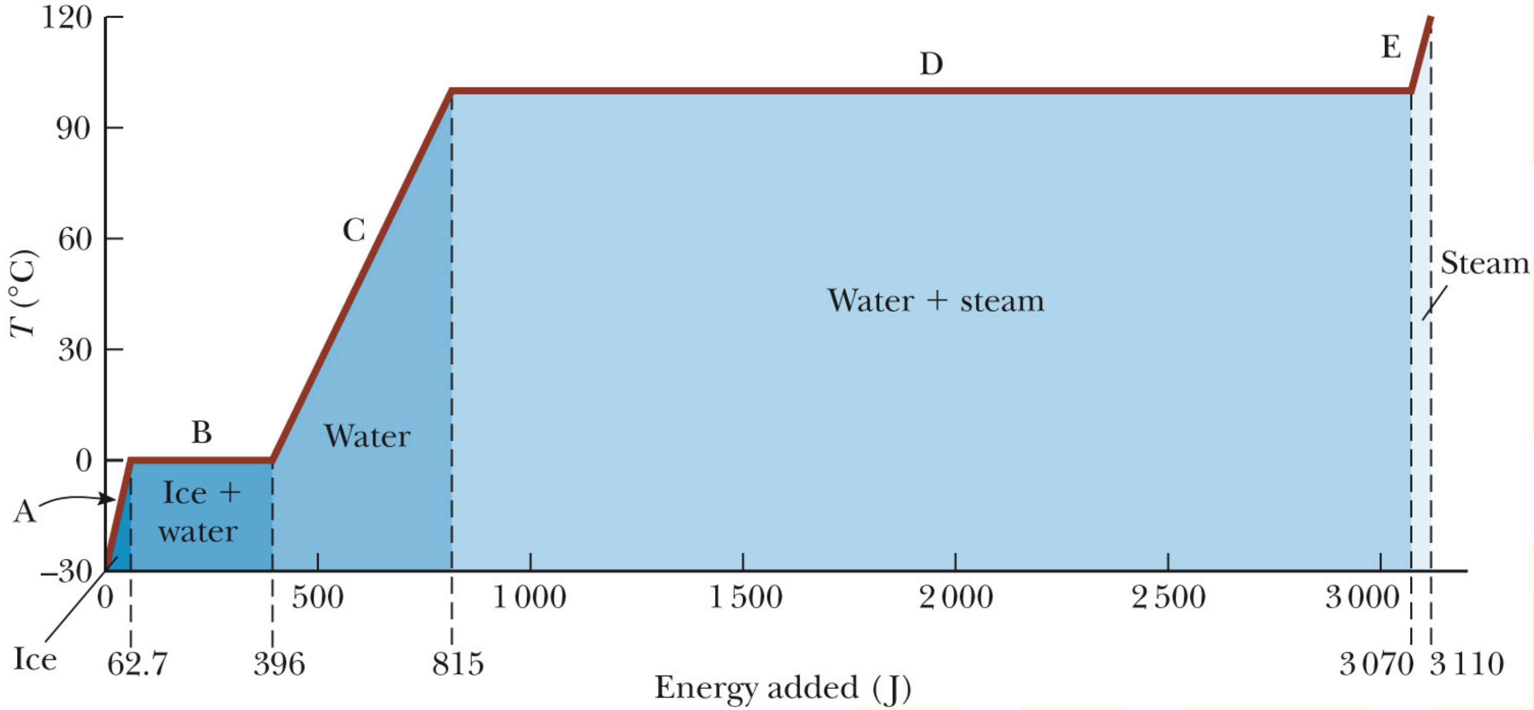
Table 11.2 Latent Heats of Fusion and Vaporization

Substance	Melting Point (°C)	Latent Heat of Fusion (J/kg)	cal/g	Boiling Point (°C)	Latent Heat of Vaporization (J/kg)	cal/g
Helium	−269.65	5.23×10^3	1.25	−268.93	2.09×10^4	4.99
Nitrogen	−209.97	2.55×10^4	6.09	−195.81	2.01×10^5	48.0
Oxygen	−218.79	1.38×10^4	3.30	−182.97	2.13×10^5	50.9
Ethyl alcohol	−114	1.04×10^5	24.9	78	8.54×10^5	204
Water	0.00	3.33×10^5	79.7	100.00	2.26×10^6	540
Sulfur	119	3.81×10^4	9.10	444.60	3.26×10^5	77.9
Lead	327.3	2.45×10^4	5.85	1 750	8.70×10^5	208
Aluminum	660	3.97×10^5	94.8	2 450	1.14×10^7	2 720
Silver	960.80	8.82×10^4	21.1	2 193	2.33×10^6	558
Gold	1 063.00	6.44×10^4	15.4	2 660	1.58×10^6	377
Copper	1 083	1.34×10^5	32.0	1 187	5.06×10^6	1 210

Transition: Solid - Liquid

Transition: Liquid - Gas

Example: Phase changes and latent heat



How much energy is required to change 1 g of ice at -30 °C to steam at 120 °C?

The pressure is kept constant.

3 ways to transfer heat

1. Conduction:

Energy is transferred by collisions between individual atoms.

Less energetic particles gain energy from more energetic particles.

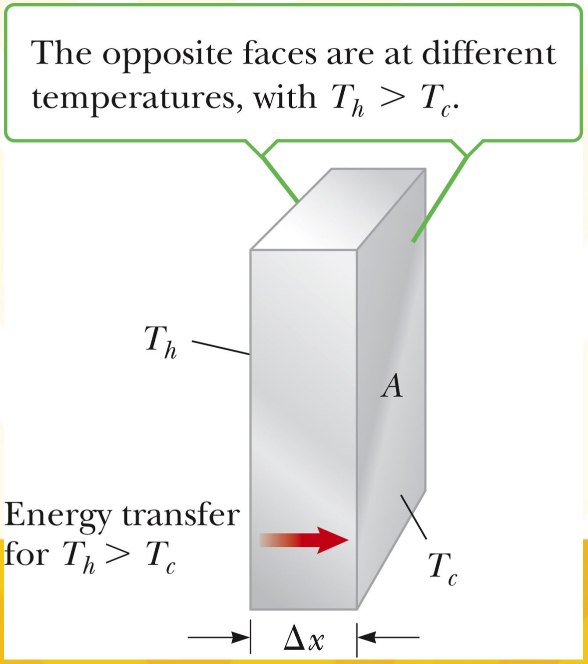
The rate of conduction depends on the properties of the substance:

- A large number of free particles that can move easily will increase the rate.
- There must be a temperature difference

The rate of energy transfer due to conduction is:

$$\boxed{P = \frac{Q}{\Delta t} = kA\frac{T_h - T_c}{\Delta x}}$$

k is a material specific constant called thermal conductivity.

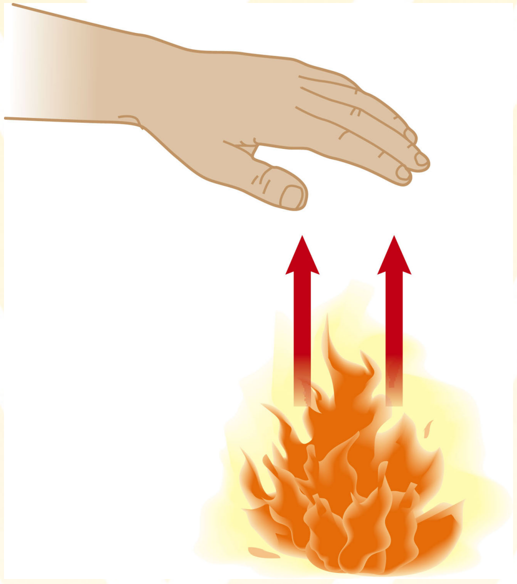


3 ways to transfer heat

2. Convection:

Energy is transferred by the movement of the whole substance.

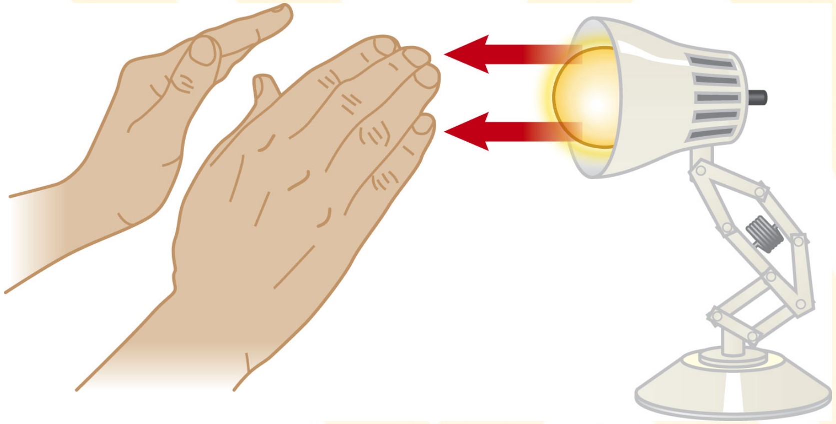
Example: Rising hot air above a fire or lamp due to the Archimedes Principle.



Other applications

- Boiling water
- Radiator

3 ways to transfer heat



3. Radiation:

Energy is transferred by electromagnetic waves. No physical contact between objects is required.

The rate of energy transfer from an object at temperature T in a surrounding at temperature T_0 by radiation is determined by Stefan's law:

$$\boxed{P = \sigma A e (T^4 - T_0^4)}$$

$\sigma = 5.669 \times 10^{-8}\ \mathrm{W/m^2\,K^4}$ and e is a material specific constant called emissivity.

Application: Thermos bottle

Goal: Good thermal isolation

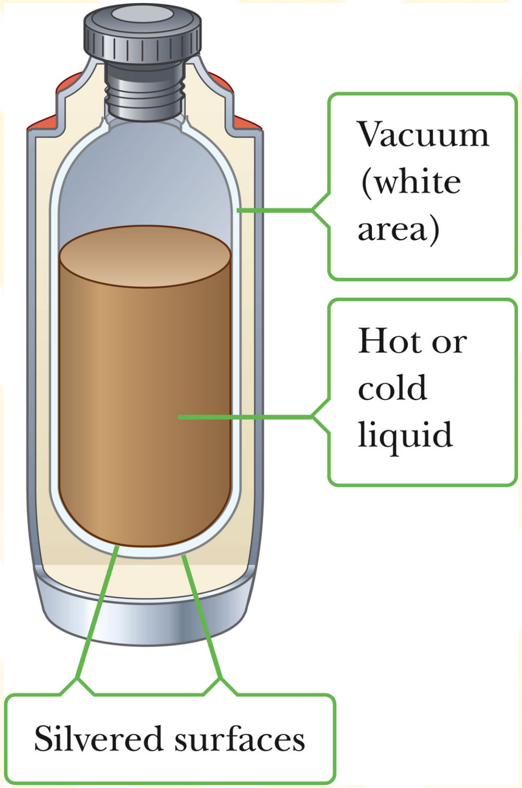
Minimize energy transfer between inside and outside by all three mechanisms.

Minimize conduction + convection:

Double walls with evacuated layer in between (no particles to carry energy).

Minimize radiation:

Silvered walls to reflect radiation and keep it inside the bottle.

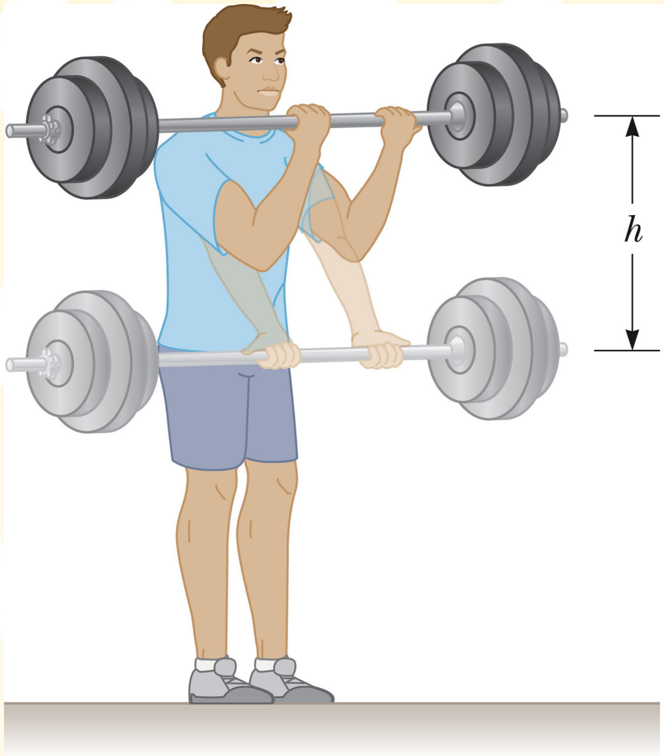


Example problem: Working Off Breakfast

A student eats a breakfast consisting of a bowl of cereal and milk, containing a total of 320 Calories of energy. He wishes to do an equivalent amount of work in the gym by performing curls with a 25 kg barbell.

How many times must he raise the weight to expend that much energy?

Assume he raises it through a vertical distance of 0.4 m each time.



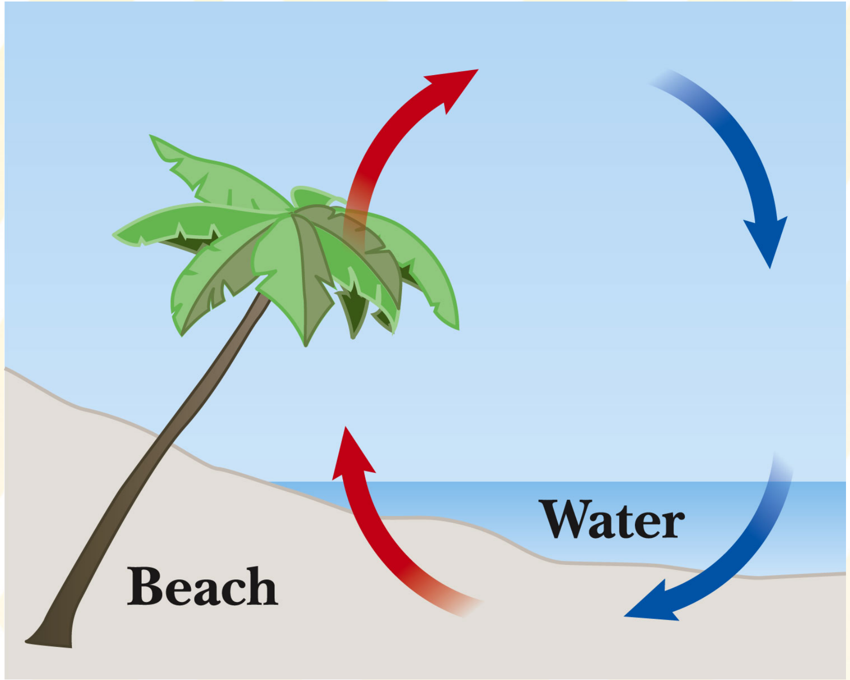
Specific heat: Applications

On a hot day, the sun adds equal amounts of energy to a beach and the nearby water.

Water has a higher specific heat compared than sand.

→ The air above the land warms faster

→ The warmer air is less dense and flows upward (Archimedes Principle) and cooler air moves toward the beach from the ocean.



The hot air cools down at higher altitudes and sinks again.

This mechanism creates a nice coole breeze from ocean to land.