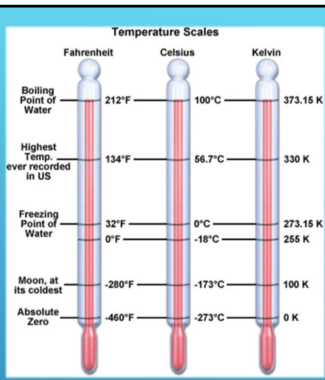

CHAPTER 17

Temperature and Heat

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Thermodynamics

- Temperature
- Heat
- Internal energy

Outline

1. Temperature and the Zeroth Law of Thermodynamics
2. Thermometers and Temperature scales
3. Thermal Expansion of Solids and Liquids
4. Heat
5. Calorimetry and Phase Changes
6. Mechanisms of Heat Transfer

1. Temperature and the Zeroth Law of Thermodynamics
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1. Temperature and Zeroth law of thermodynamics

Thermal Contact

3 Two objects are in thermal contact with each other if energy can be exchanged between them.

- ➢ The exchanges we will focus on will be in the form of heat or electromagnetic radiation.
- ➢ The energy is exchanged due to a temperature difference.

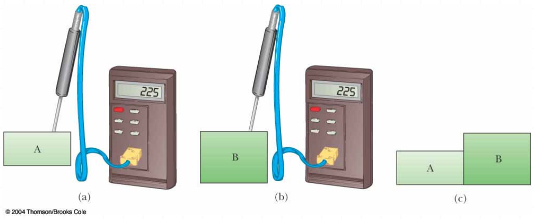
Thermal Equilibrium

3 Thermal equilibrium is a situation in which two objects would have no net exchange of energy by heat or electromagnetic radiation if they were placed in thermal contact.

3 The thermal contact does not have to be physical contact.

Zeroth Law of Thermodynamics – the Law of Equilibrium

- If objects A and B are separately in thermal equilibrium with a third object C, then A and B are in thermal equilibrium with each other.



- Two systems are in thermal equilibrium if and only if they have the same temperature.

Temperature

- Temperature can be thought of as the property that determines whether an object is in thermal equilibrium with other objects .
- Two objects in thermal equilibrium with each other are at the same temperature.
- Can a particle such as an electron have any temperature ? No. Temperature is meaningless for a one-particle system.

Q: Two objects, with different sizes, masses, and temperatures, are placed in thermal contact. Energy travels

(a) from the larger object to the smaller object

(b) from the object with more mass to the one with less

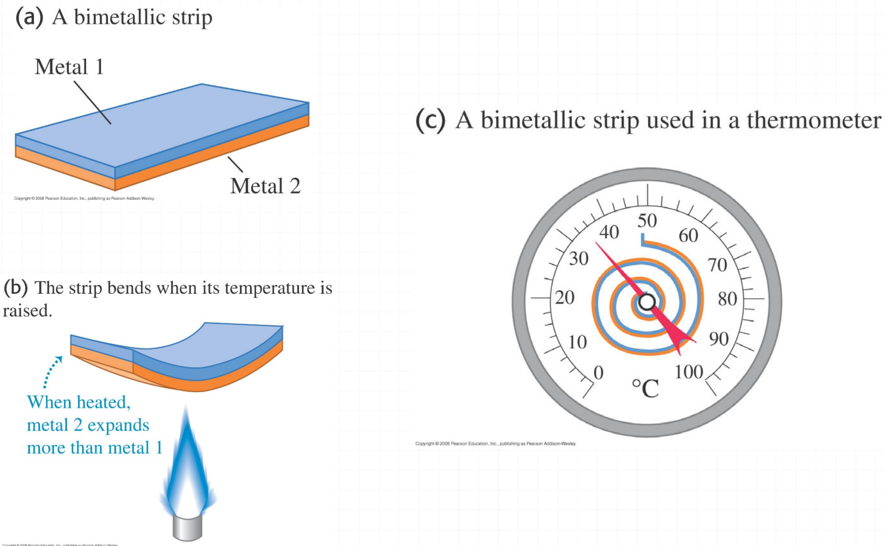
(c) from the object at higher temperature to the object at lower temperature.

A: (c)

2. Thermometers and Temperature Scales

Thermometers

- A thermometer is a device that is used to measure the temperature of a system.
- Thermometers are based on the principle that some physical property of a system changes as the system's temperature changes.
  - The volume of a liquid.
  - The dimensions of a solid.
  - The pressure of a gas at a constant volume.
  - The volume of a gas at a constant pressure.
  - The electric resistance of a conductor.
  - The color of an object.
  - The thermal radiation.



Celsius Temperature Scale (centigrade)

- The ice point of water is defined to be 0^{o} C.
- The steam point of water is defined to be 100^{o} C.
- The length between these two points is divided into 100 increments, called degrees.

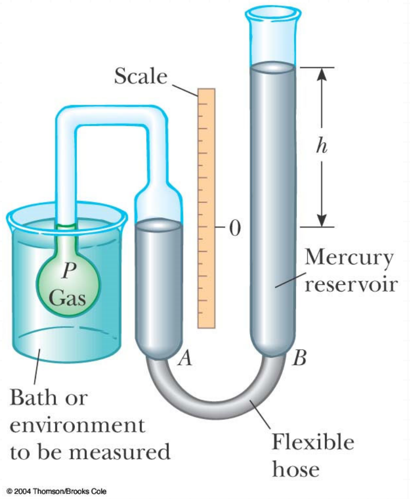
Fahrenheit temperature scale

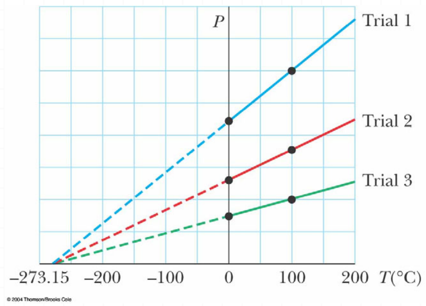
- The ice point of water is defined to be 32^{o} F.
- The steam point of water is defined to be 212^{o} F.
- The length between these two points is divided into 180 increments:

$$T_F = \frac{9}{5}T_C + 32^{\circ} F$$

- $T_F = 100\ ^{o}$F, when $T_C = 38\ ^{o}$C.

The Constant Volume Gas Thermometer





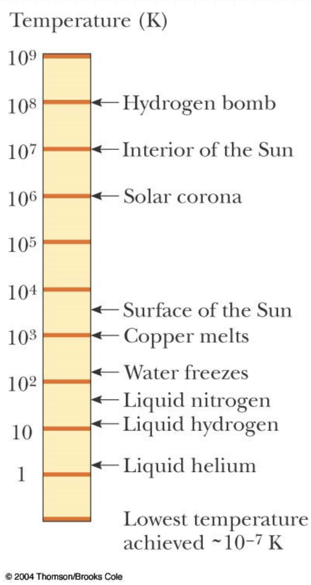
↑ Absolute zero

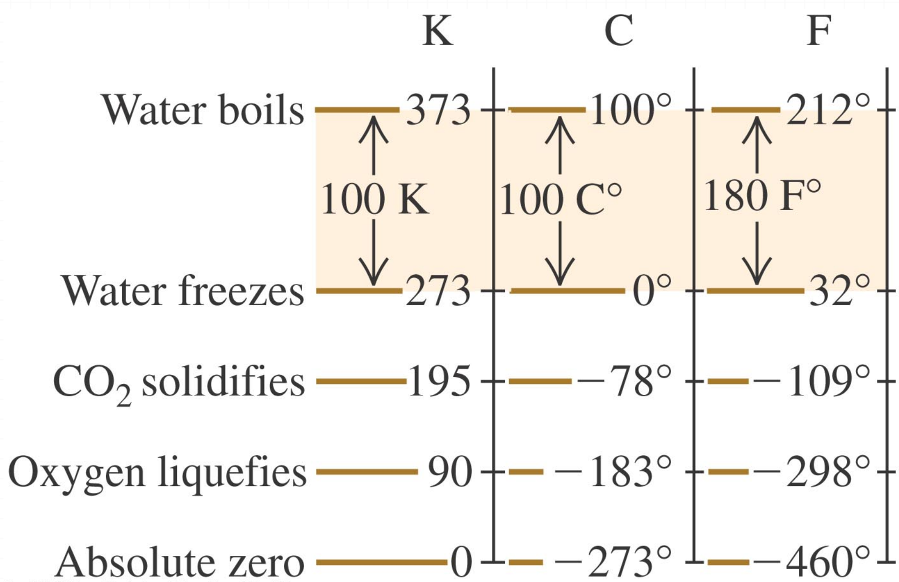
Absolute Temperature Scale

3 Absolute zero is used as the basis of the absolute temperature scale.

- ➢ $T_{\text{Celsius}} = T - 273.15.$
- ➢ The unit of the absolute is **kelvin.**

😎 The temperature for the triple point of water is 273.16 K.



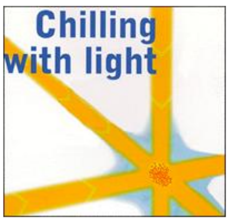


The Nobel Prize in Physics 1997

The Royal Swedish Academy of Sciences has awarded the 1997 Nobel Prize in Physics jointly to

Steven Chu, Claude Cohen-Tannoudji and William D. Phillips

for their developments of methods to cool and trap atoms with laser light.

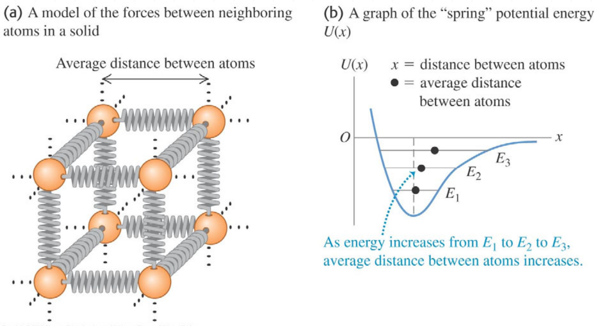


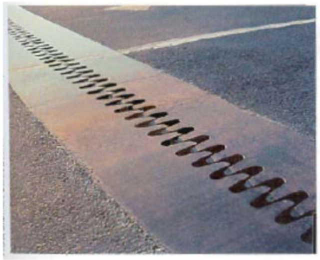
This year's Nobel laureates in physics have developed methods of cooling and trapping atoms by using laser light. Their research is helping us to study fundamental phenomena and measure important physical quantities with unprecedented precision.

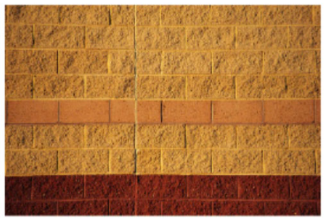
3. Thermal expansion of Solids and Liquids

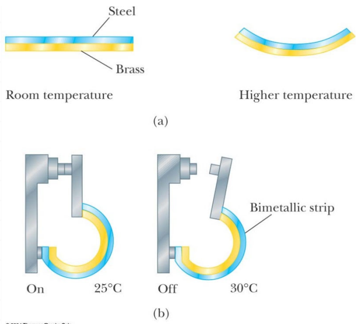
Thermal Expansion

- Thermal expansion is the increase in the size of an object with an increase in its temperature.
- Thermal expansion is a consequence of the change in the average separation between the atoms in an object.









Linear Expansion

3 Assume an object has an initial length L_i.

3 That length increases by ΔL as the temperature changes by ΔT.

3 We define the coefficient of linear expansion as

- $\Delta L = \alpha L_i \Delta T, \quad \alpha \equiv \dfrac{\Delta L / L_i}{\Delta T}$
- unit: $(^{o}\mathrm{C})^{-1}$.
- α depends on temperature. The linear relation is only good for a small temperature range.
- only for solids and liquids.

3 Some materials expand along one dimension, but contract along another as the temperature increases, α is not always positive. e.g., $CaCO_3$, rubber, heat shrink tube.

Average Expansion Coefficients for Some Materials Near Room Temperature

Material (Solids)	Average Linear Expansion Coefficient $(\alpha)(°C)^{-1}$	Material (Liquids and Gases)	Average Volume Expansion Coefficient $(\beta)(°C)^{-1}$
Aluminum	24×10^{-6}	Acetone	1.5×10^{-4}
Brass and bronze	19×10^{-6}	Alcohol, ethyl	1.12×10^{-4}
Concrete	12×10^{-6}	Benzene	1.24×10^{-4}
Copper	17×10^{-6}	Gasoline	9.6×10^{-4}
Glass (ordinary)	9×10^{-6}	Glycerin	4.85×10^{-4}
Glass (Pyrex)	3.2×10^{-6}	Mercury	1.82×10^{-4}
Invar (Ni–Fe alloy)	0.9×10^{-6}	Turpentine	9.0×10^{-4}
Lead	29×10^{-6}	Air[a] at 0°C	3.67×10^{-3}
Steel	11×10^{-6}	Helium[a]	3.665×10^{-3}

[a]Gases do not have a specific value for the volume expansion coefficient because the amount of expansion depends on the type of process through which the gas is taken. The values given here assume the gas undergoes an expansion at constant pressure.

Thermal stress induced by temperature change

$$(1)\ \left(\frac{\Delta L}{L_i}\right)_{\text{Thermal}} = \alpha \Delta T$$

$$(2)\ \text{Young's modulus}\ \ Y = \frac{F/A}{\Delta L / L_i} \Rightarrow \left(\frac{\Delta L}{L_i}\right)_{\text{Tension}} = \frac{F/A}{Y}$$

If the total length is kept fixed,

$$\left(\frac{\Delta L}{L_i}\right)_{\text{Thermal}} + \left(\frac{\Delta L}{L_i}\right)_{\text{Tension}} = 0$$

$$\Rightarrow \text{Thermal stress}: \frac{F}{A} = -(\alpha \Delta T) Y$$

https://www.facebook.com/theactionlabofficial/videos/308285330859254

Volume Expansion

3 The change in volume is proportional to the original volume and to the change in temperature.

- $\Delta V = \beta V_i \Delta T$.
- β is the coefficient of volume expansion.

3 For a solid, $\boldsymbol{\beta = 3\alpha}$, assuming the material is isotropic.

Proof:

$$V_i + \Delta V = (l_i + \Delta l)(w_i + \Delta w)(h_i + \Delta h)$$

$$= (l_i + \alpha l_i \Delta T)(w_i + \alpha w_i \Delta T)(h_i + \alpha h_i \Delta T)$$

$$= l_i w_i h_i (1 + \alpha \Delta T)^3$$

$$= V_i \left[1 + 3\alpha \Delta T + 3(\alpha \Delta T)^2 + (\alpha \Delta T)^3 \right]$$

$$\Rightarrow \quad \frac{\Delta V}{V_i} = \underbrace{3\alpha}_{\equiv \beta} \Delta T + 3(\underbrace{\cancel{\alpha \Delta T}}_{\because \alpha\Delta T \ll 1})^2 + (\underbrace{\cancel{\alpha \Delta T}}_{\because \alpha\Delta T \ll 1})^3$$

Q: Two spheres are made of the same metal and have the same radius, but one is hollow and the other is solid. The spheres are taken through the same temperature increase. Which sphere expands more?

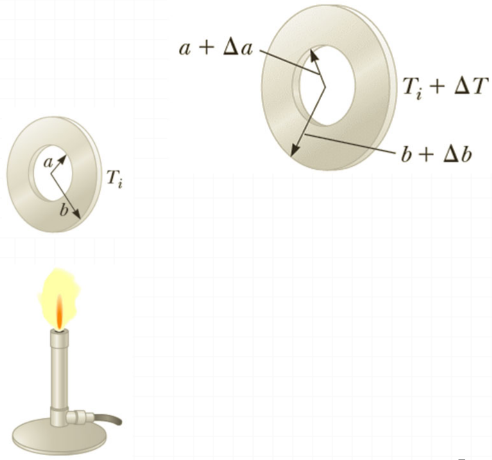
(a) solid sphere.

(b) hollow sphere.

(c) They expand by the same amount.

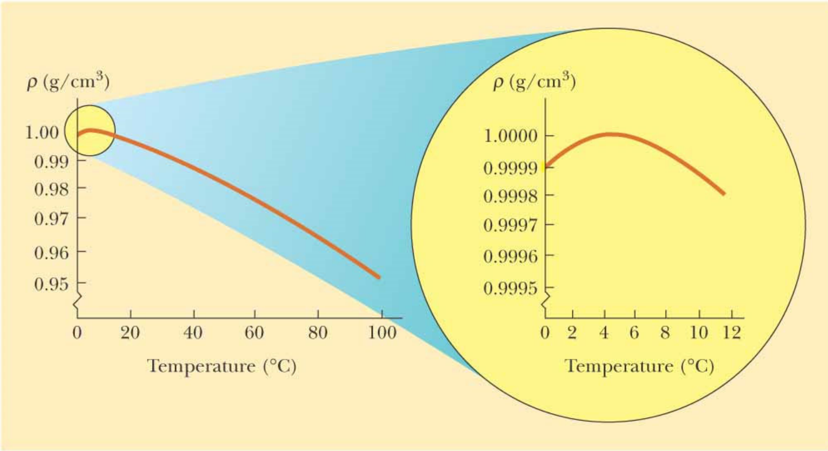
(d) not enough information to say.

A: (c)



The unusual behavior of water

- As the temperature decreases from 4ºC to 0ºC, water volume expands and its density decreases. Cold water and ice float on top and warm water stays at the bottom.
- Above 4ºC, water expands with increasing temperature, and its density decreases.
- The maximum density of water (1.000 g/cm^3) occurs at 4ºC.



It explains why ice floats on water.

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Heat

3 Heat (Q) is defined as the transfer of energy across the boundary of a system due to a temperature. difference between the system and its surroundings.

3 The term *heat* will also be used to represent the *amount* of energy transferred by this method.

Units of Heat

3 The calorie is the unit used for heat.

- ➢ One calorie is the amount of energy transfer necessary to raise the temperature of 1 g of water from 14.5°C to 15.5°C.

3 In the US Customary system, the unit is a BTU (British Thermal Unit).

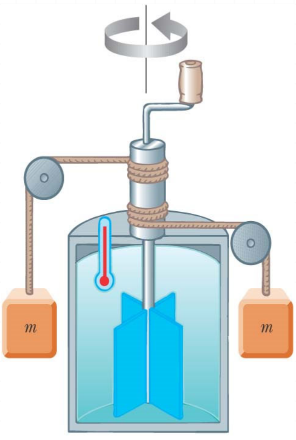
- ➢ One BTU is the amount of energy transfer necessary to raise the temperature of 1 lb of water from 63°F to 64°F.

3 The SI unit is to use Joules.

- ➢ **1 cal = 4.186 J**
- ➢ **1BTU = 1055 J**

Mechanical Equivalent of Heat

- Joule established the equivalence between mechanical energy and internal energy.
- The loss in potential energy associated with the blocks equals the work done by the paddle wheel on the water.



Heat Capacity

- The heat capacity, C, of a particular sample is defined as the amount of energy needed to raise the temperature of that sample by 1°C.
- If energy Q only produces a change of temperature of ΔT and does NOT convert into other energy such as work and potential energy, then $Q = C\Delta T$.

Specific Heat

3 Specific heat, c, is the heat capacity per unit mass.

3 If energy Q transfers to a sample of a substance of mass m and the temperature changes by ΔT, then the specific heat is

$$c \equiv \frac{C}{m} = \frac{Q}{m\Delta T}$$

Substance	Specific heat c J/kg · °C	cal/g · °C
Elemental solids		
Aluminum	900	0.215
Beryllium	1 830	0.436
Cadmium	230	0.055
Copper	387	0.092 4
Germanium	322	0.077
Gold	129	0.030 8
Iron	448	0.107
Lead	128	0.030 5
Silicon	703	0.168
Silver	234	0.056
Other solids		
Brass	380	0.092
Glass	837	0.200
Ice (−5°C)	2 090	0.50
Marble	860	0.21
Wood	1 700	0.41
Liquids		
Alcohol (ethyl)	2 400	0.58
Mercury	140	0.033
Water (15°C)	4 186	1.00
Gas		
Steam (100°C)	2 010	0.48

Molar specific heat

$$Q = n c_n \Delta T$$

c_n : molar specific heat

n : number of moles

$$n = \frac{m}{M}, \quad M : \text{ molar mass}$$

$$\left.\begin{aligned} Q &= \frac{m}{M} c_n \Delta T \\ &= mc\Delta T \end{aligned}\right\} \Rightarrow c_n = Mc$$

5. Calorimetry and Phase Changes

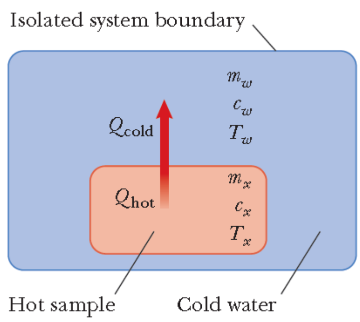
Calorimetry

3 Conservation of energy requires that the amount of energy that leaves the sample equals the amount of energy that enters the water

➢ $Q_{\text{cold}} = -Q_{\text{hot}}$

$$\Rightarrow \quad m_w c_w (T_f - T_w) = -m_x c_x (T_f - T_x)$$

$$\Rightarrow \quad c_x = \frac{m_w c_w (T_f - T_w)}{m_x (T_x - T_f)}$$



Phase Changes

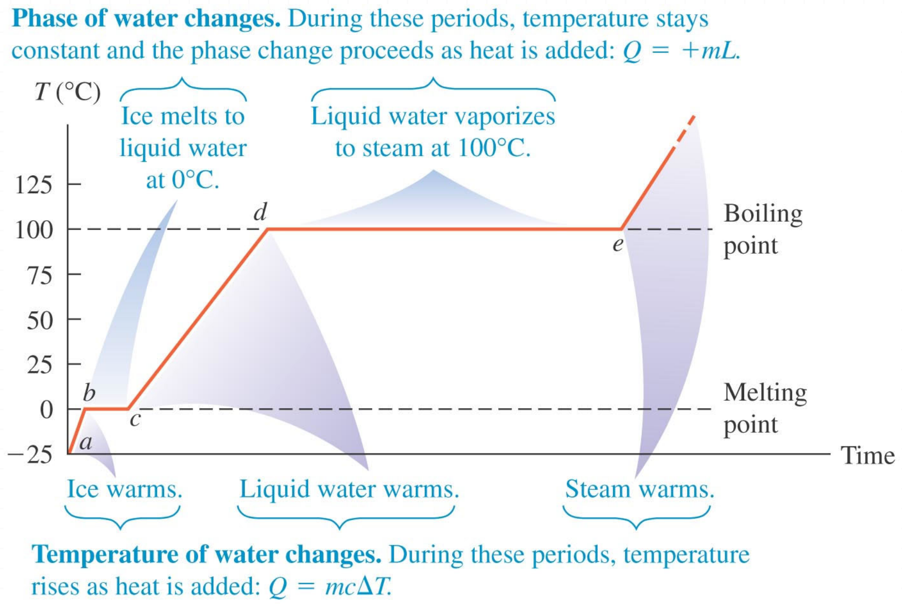
3 A phase change is when a substance changes from one form to another.

3 Two common phase changes are

➢ Solid to liquid (melting).

➢ Liquid to gas (boiling).

3 Certain phase changes involve a change in internal energy but there is no change in temperature of the substance.



Latent Heat

3 If an amount of energy Q is required to change the phase of a sample of mass m,

$$Q = \pm mL$$

- The quantity L is called the **latent heat** of the material.

$$E_{\text{int}} = \underbrace{\text{thermal energy}}_{\substack{\text{Kinetic energy} \\ \to \text{Temperature}}} + \underbrace{\text{Bond energy}}_{\substack{\text{Potential energy} \\ \to \text{Phase transition, latent heat}}}$$

$$\Delta E_{\text{int}} = (\frac{1}{2} nR\Delta T) \times f \pm nL$$

- The *latent heat of fusion/solidification* is used when the phase change is between solid and liquid.
- The *latent heat of vaporization/condensation* is used when the phase change is from liquid to gas.
- The latent heat of vaporization is greater than the latent heat of fusion.

Sample Latent Heat Values

Latent Heats of Fusion and Vaporization

Substance	Melting Point (°C)	Latent Heat of Fusion (J/kg)	Boiling Point (°C)	Latent Heat of Vaporization (J/kg)
Helium	− 269.65	5.23×10^3	− 268.93	2.09×10^4
Nitrogen	− 209.97	2.55×10^4	− 195.81	2.01×10^5
Oxygen	− 218.79	1.38×10^4	− 182.97	2.13×10^5
Ethyl alcohol	− 114	1.04×10^5	78	8.54×10^5
Water	0.00	3.33×10^5	100.00	2.26×10^6
Sulfur	119	3.81×10^4	444.60	3.26×10^5
Lead	327.3	2.45×10^4	1 750	8.70×10^5
Aluminum	660	3.97×10^5	2 450	1.14×10^7
Silver	960.80	8.82×10^4	2 193	2.33×10^6
Gold	1 063.00	6.44×10^4	2 660	1.58×10^6
Copper	1 083	1.34×10^5	1 187	5.06×10^6

😎 Latent heat is not correlated with the melting point and boiling point.

😎 The metal gallium has a low melting temperature 29.8 °C.

https://www.youtube.com/watch?v=-SGscd2KIjE

Supercooling and superheating

3 If liquid water is held perfectly still in a very clean container, it is possible for the water to drop below 0°C without freezing into ice. This phenomenon, called **supercooling**.

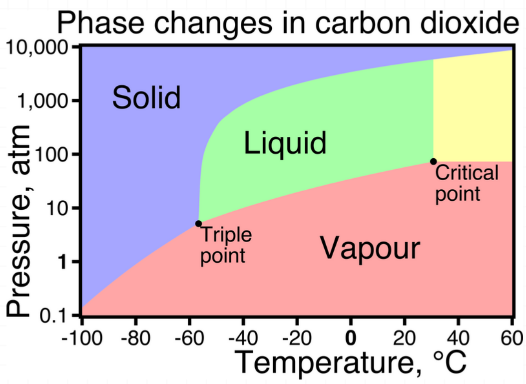
- If supercooled water is disturbed, it suddenly freezes. The system drops into the lower-energy configuration of bound molecules of the ice structure, and the energy released raises the temperature back to 0°C.
- Commercial Hand warmers are an example.

3 It is also possible to create **superheating.** For example, clean water in a very clean cup placed in a microwave oven can sometimes rise in temperature beyond 100°C without boiling because the formation of a bubble of steam in the water requires scratches in the cup or some type of impurity in the water to serve as a nucleation site.

https://www.facebook.com/watch/?v=1799173086925334

https://www.youtube.com/watch?v=NMSxuORKynI
https://www.youtube.com/watch?v=ph8xusY3GTM

Supercritical fluid – CO_2



http://www.chemistry-blog.com/2009/02/04/chemistry-lab-demonstrations-liquid-co2-extraction/
https://www.youtube.com/watch?v=GEr3NxsPTOA&t=108s

Ex. Liquid helium has a very low boiling point, 4.2 K, and a very low latent heat of vaporization, 2.09×10^4 J/kg. If energy is transferred to a container of boiling liquid helium from an immersed electric heater at a rate of 10.0 W, how long does it take to boil away 1.00 kg of the liquid?

Ans:

$$L_v = 2.09 \times 10^4 \text{ J/kg}$$

$$\Rightarrow \quad \Delta E = mL_v = 2.09 \times 10^4 \text{ J}$$

$$\Delta t = \frac{\Delta E}{P} = \frac{2.09 \times 10^4 \text{ J}}{10.0 \text{ J/s}} = 2.09 \times 10^3 \text{ s}$$

Ex. A heavy copper pot of mass 2.0 kg (including the copper lid) is at a temperature of 150 $^{\circ}$C. You pour 0.10 kg of water at 25 $^{\circ}$C into the pot, then quickly close the lid of the pot so that no steam can escape. Find the final temperature of the pot and its contents, and determine the phase (liquid or gas) of the water. Assume that no heat is lost to the surroundings.

Ans:

3 possible outcomes:

1. $T_f < 100\ ^{\circ}$C, liquid

2. $T_f = 100\ ^{\circ}$C, liquid + steam

3. $T_f \geq 100\ ^{\circ}$C, steam

Case 1:

$$Q_{H_2O} + Q_{Cu} = m_{H_2O} c_{H_2O} (T_f - 25) + m_{Cu} c_{Cu} (T_f - 150) = 0$$
$$\Rightarrow \quad T_f = 106 > 100, \quad \text{violates the premise.}$$

Case 2:

$$Q_{H_2O} + Q_{Cu} = \left[m_{H_2O} c_{H_2O} (100 - 25) + x m_{H_2O} L \right] + \left[m_{Cu} c_{Cu} (100 - 150) \right]$$
$$\Rightarrow \quad x = 0.034 < 1, \text{ acceptible solution.}$$

If $x > 1$, then continue to try Case 3!

6. Mechanisms of Heat Transfer

Mechanisms of Heat Transfer

3 Conduction

3 Convection

3 Radiation

Conduction

3 The thermal conduction process can be viewed on an atomic scale, as an exchange of kinetic energy between microscopic particles by collisions.

- The microscopic particles can be atoms, molecules or free electrons.
- Rate of conduction depends upon the characteristics of the substance.

3 In general, metals are good conductors.

- They contain large numbers of electrons that are relatively free to move through the metal.
- Poor conductors include asbestos, paper, and gases.

3 Conduction can occur only if there is a difference in temperature between two parts of the conducting medium.

Law of thermal conduction

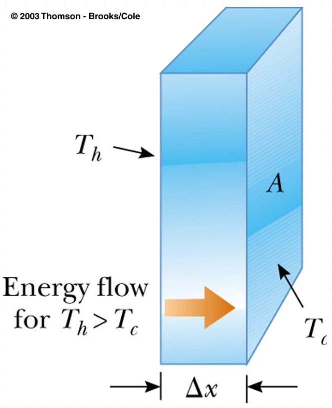
3 The rate of transfer P is given by:

$$P = \frac{Q}{\Delta t} \propto A\frac{\Delta T}{\Delta x}$$

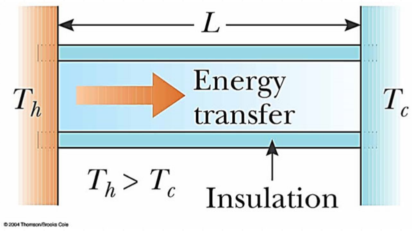
$$\Rightarrow P = kA\left|\frac{dT}{dx}\right|$$

k: thermal conductivity

$\left|\frac{dT}{dx}\right|$: temperature gradient



Temperature Gradient



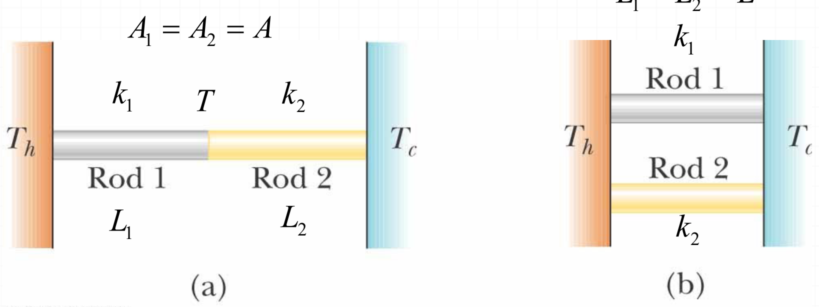
For a steady state and k is independent of temperature,

$$\Rightarrow \left|\frac{dT}{dx}\right| = \frac{T_h - T_c}{L}$$

Substance	Thermal Conductivity (W/m · °C)
Metals (at 25°C)	
Aluminum	238
Copper	397
Gold	314
Iron	79.5
Lead	34.7
Silver	427
Nonmetals (approximate values)	
Asbestos	0.08
Concrete	0.8
Diamond	2 300
Glass	0.8
Ice	2
Rubber	0.2
Water	0.6
Wood	0.08
Gases (at 20°C)	
Air	0.023 4
Helium	0.138
Hydrogen	0.172
Nitrogen	0.023 4
Oxygen	0.023 8

Ex. Energy Transfer Through Two Slabs

Two slabs of thickness L_1 and L_2 and thermal conductivities k_1 and k_2 are in thermal contact with each other, as shown in Figure. The temperatures of their outer surfaces are T_c and T_h, respectively, and $T_h > T_c$. Determine the temperature at the interface and the rate of energy transfer by conduction through the slabs in the steady-state condition.



Ans:

(a) $$P_1 = k_1 A\left(\frac{T_h - T}{L_1}\right) = P_2 = k_2 A\left(\frac{T - T_c}{L_2}\right) = P = kA\left(\frac{T_h - T_c}{L_1 + L_2}\right)$$

$$\Rightarrow \quad T = \frac{k_1 L_2 T_c + k_2 L_1 T_h}{k_1 L_2 + k_2 L_1}$$

$$P = \frac{A(T_h - T_c)}{(L_1 / k_1) + (L_2 / k_2)}$$

$$k = \frac{L_1 + L_2}{(L_1 / k_1) + (L_2 / k_2)}$$

(b)

$$P = P_1 + P_2$$

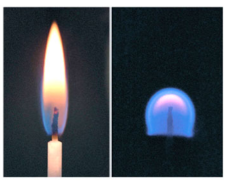
$$\Rightarrow \quad kA\left(\frac{T_h - T_c}{L}\right) = k_1 A_1\left(\frac{T_h - T_c}{L}\right) + k_2 A_2\left(\frac{T_h - T_c}{L}\right)$$

$$\Rightarrow \quad kA = k_1 A_1 + k_2 A_2$$

Convection

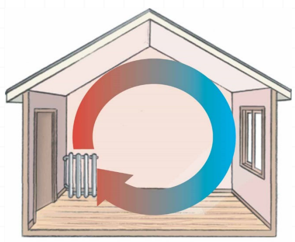
3 Energy transferred by the movement of a substance.

- When the movement results from differences in density, it is called *natural convection*.
- When the movement is forced by a fan or a pump, it is called *forced convection*.



(a) (b)

(both): NASA Glenn Research Center



Radiation emission

3 All objects radiate energy continuously in the form of electromagnetic waves due to thermal vibrations of their molecules.

3 Rate of radiation is given by Stefan's law: $P = \sigma AeT^4$

- P is the rate of energy transfer, in Watts.
- σ = 5.6696 x 10^{-8} W/m$^2 \cdot$ K^4.
- A is the surface area of the object.
- e is a constant called the **emissivity**.
- e varies from 0 to 1.
- T is the temperature in Kelvins.

Radiation absorption

In equilibrium, the power of emission = the power of absorption,

$$P_{\text{absorption}} = P_{\text{emission}} = \sigma AeT^4$$

Energy Absorption and Emission by Radiation

3 With its surroundings, the rate at which the object at temperature T with surroundings at T_o radiates is

- $P_{net} = \sigma Ae\,(T^4 - T_o^4)$.

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Ideal Absorbers/ Ideal Reflector

3 An *ideal absorber* is defined as an object that absorbs all of the energy incident on it.

- $e = 1$.
- This type of object is called a black body.
- An ideal absorber is also an ideal radiator of energy.

3 An ideal reflector absorbs none of the energy incident on it.

- $e = 0$

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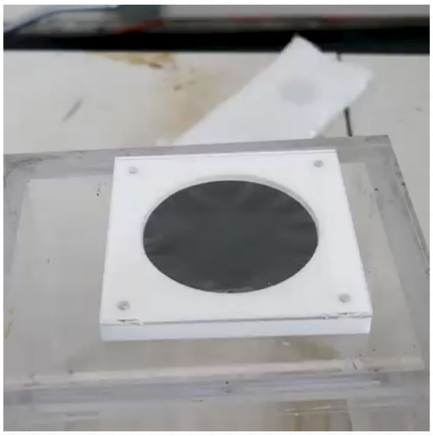


Ex. A student is trying to decide what to wear. The surroundings (his bedroom) are at 20.0 °C. If the skin temperature of the unclothed student is 35 °C, what is the net energy loss from his body in 10.0 min by radiation? Assume that the emissivity of skin is 0.900 and that the surface area of the student is 1.50 m^2.

Ans:

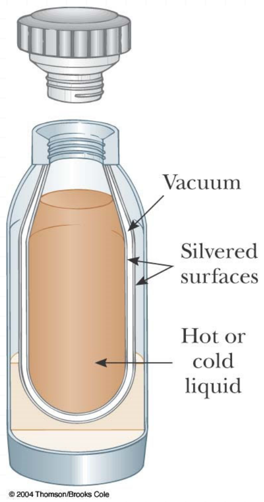
$$\begin{aligned} P_{net} &= \sigma A e (T^4 - T_0^4) \\ &= 5.67 \times 10^{-8}\ \text{W/m}^2 \cdot K^4)(1.5\ \text{m}^2) \times 0.9 \times [(308\ \text{K})^4 - (293\ \text{K})^4] \\ &= 125\ \text{W} \end{aligned}$$

$$Q = P_{net} \Delta t = (125\ \text{W})(600\ \text{s}) = 7.5 \times 10^4\ \text{J}$$

The Dewar Flask

3 A Dewar flask is a container designed to minimize the energy losses by conduction, convection, and radiation.

3 A Thermos bottle is a common household equivalent of a Dewar flask.



Dewar

radiation baffle

超導磁鐵

https://www.facebook.com/watch/?ref=saved&v=1369992506854607

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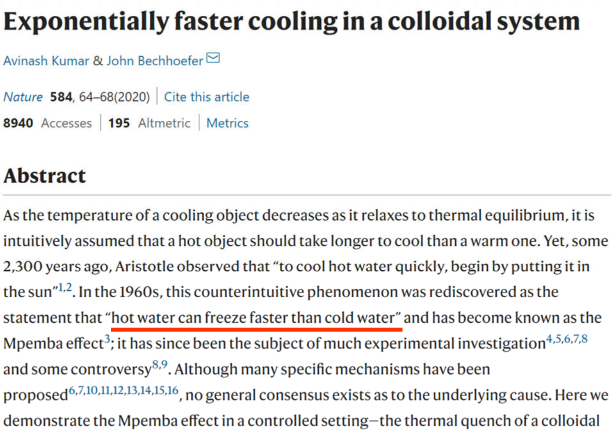
一碗冰淇淋惹出的大麻煩！熱水結冰比冷水快？半世紀爭議終於解開
[https://pansci.asia/archives/190853]

Mpemba effect



Exponentially faster cooling in a colloidal system

Avinash Kumar & John Bechhoefer

Nature **584**, 64–68(2020) | Cite this article

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Abstract

As the temperature of a cooling object decreases as it relaxes to thermal equilibrium, it is intuitively assumed that a hot object should take longer to cool than a warm one. Yet, some 2,300 years ago, Aristotle observed that "to cool hot water quickly, begin by putting it in the sun"[1,2]. In the 1960s, this counterintuitive phenomenon was rediscovered as the statement that "hot water can freeze faster than cold water" and has become known as the Mpemba effect[3]; it has since been the subject of much experimental investigation[4,5,6,7,8] and some controversy[8,9]. Although many specific mechanisms have been proposed[6,7,10,11,12,13,14,15,16], no general consensus exists as to the underlying cause. Here we demonstrate the Mpemba effect in a controlled setting–the thermal quench of a colloidal

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Phonons leap a nanoscale gap

The Casimir effect mediates heat transfer across a vacuum without photons.

Heather Hill

0 COMMENTS

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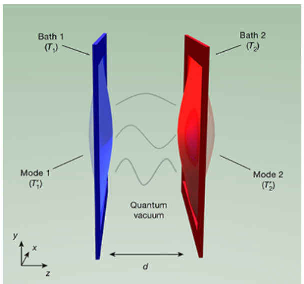
Phonons by definition require a material to propagate—lattice vibrations can't happen without a lattice. Yet for a decade theorists have suspected that a phonon could move across a vacuum gap between two materials with the help of a quantum effect known as the Casimir force. Now Xiang Zhang of the University of California, Berkeley, and his colleagues have observed for the first time a phonon moving between two materials spaced hundreds of nanometers apart. Because phonons are energy carriers, the



Credit: K. Y. Fong et al., *Nature* **576**, 243 (2019)

https://physicstoday.scitation.org/do/10.1063/PT.6.1.20191217a/full/