TEMPERATURE AND HEAT

Intended Learning Outcomes – after this lecture you will learn:

1. zeroth law of thermodynamics
2. the absolute (Kelvin) temperature scale
3. thermal expansion
4. heat capacity and latent heat (revision)
5. heat transfer – conduction, convection, and radiation

Textbook Reference: Ch 17 (excluding thermal stress in 17.4)

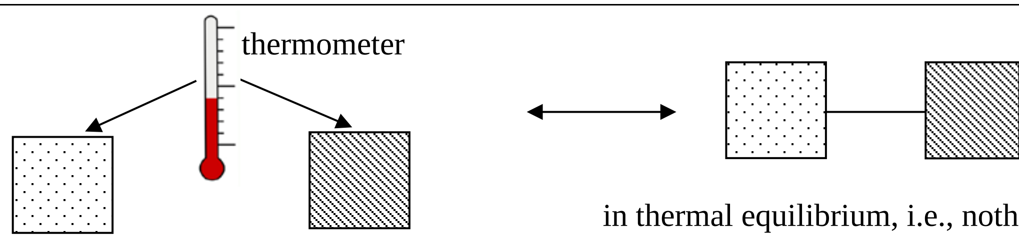
Some questions to begin with:

1) **What is temperature**? – reading from a thermometer (will give a microscopic definition for temperature in PHYS 4050).
2) **What does it mean by two bodies having the same temperature**? – the answer is in the zeroth law of thermodynamics:

Zeroth Law of Thermodynamics
If C is initially in **thermal equilibrium** (i.e., no measurable change when they are put in thermal contact) with both A and B, then A and B are also in thermal equilibrium

If C is a thermometer, then we conclude:

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



system A

system B

in thermal equilibrium, i.e., nothing changes when they are in thermal contact

⚠ If you put a thermometer in hot water, the reading is the temperature of the thermometer itself, which by the above conclusion is also the temperature of the water.

Different units of temperature:

Fahrenheit T_F $\longleftrightarrow$ $T_F = \frac{9}{5}T_C + 32$ **Celsius** T_C $\longleftrightarrow$ $T_C = T - 273.15$ **Kelvin** T (**absolute temperature**)

Fahrenheit: freezing and boiling points of water at 1 atm are 32 ^{o}F and 212 ^{o}F

Celsius: freezing and boiling points of water at 1 atm are 0 ^{o}C and 100 ^{o}C

Kelvin: **triplet point** (solid, liquid and gas forms coexist) of water is 273.16 K

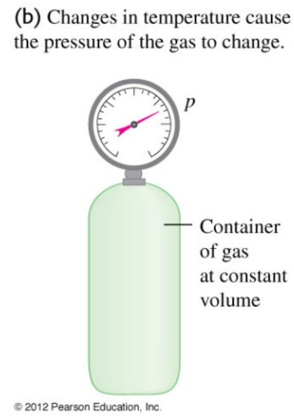
How to measure absolute temperature? **Constant volume gas thermometer**

use a dilute gas, (recall the "pressure law" from high school)

$$\frac{T_2}{T_1} = \frac{p_2}{p_1}$$

calibrate at the triplet point of water

$$T = T_{\text{triple}} \frac{p}{p_{\text{triple}}} = (273.16\text{ K}) \frac{p}{p_{\text{triple}}}$$



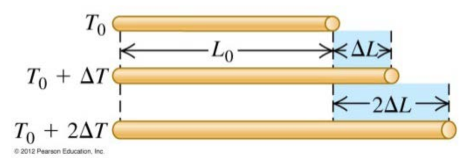
Thermal Expansion – thermal agitation causes atoms to move farther apart

Linear expansion (e.g. of a rod)

for small temperature change, assume *fractional* increase in length is proportional to ΔT,

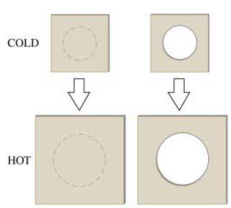
$$\frac{\Delta L}{L_0} = \alpha \Delta T$$

coefficient of linear expansion, a property of the material, unit: K^{-1}



i.e., $L = L_0 + \Delta L = L_0(1 + \alpha \Delta T)$

Question



A square with a hole cut out. Due to thermal expansion, at higher temperature the hole will be (larger / smaller).

Hint: consider the same square without the hole

Answer: see CAUTION on P. 575 of textbook

Volume expansion

Define **coefficient of volume expansion** by $\dfrac{\Delta V}{V_0} = \beta \Delta T$

suppose $\quad V = L^3, \quad dV = 3L^2 dL \quad \Rightarrow \quad \beta = \dfrac{1}{\Delta T}\dfrac{dV}{V} = \dfrac{1}{\Delta T}\dfrac{3L^2 dL}{L^3} = 3\left(\dfrac{1}{\Delta T}\dfrac{dL}{L}\right) = 3\alpha$

Quantity of Heat

Heat means energy in transit from one body to another due to temperature difference
How to quantify heat?

<u>Heat Capacity</u> – amount of heat needed to raise temperature without change of form
specific heat c defined by

$$Q = mc\Delta T$$

heat required for temperature change ΔT of mass m

If the amount of substance is n moles (1 mole = $\underbrace{6.02214 \times 10^{23}}_{\textbf{Avogadro number } N_A}$ molecules)

i.e. $m = nM$ **molar mass**, i.e., mass of 1 mole of the substance

$Q = nMc\Delta T = nC\Delta T \quad \Rightarrow \quad C = Mc$

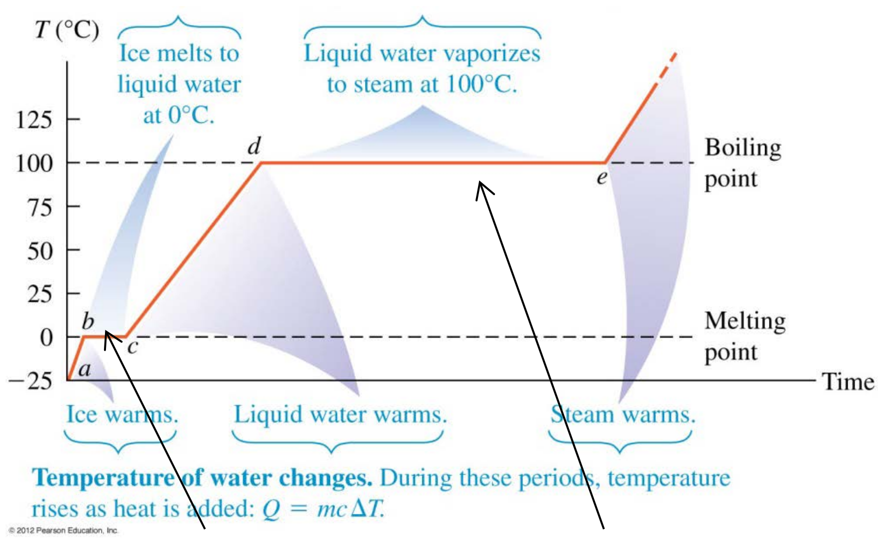
specific heat, unit: J/kg·K

molar heat capacity,
or **molar specific heat**, unit: J/mol·K

For example, specific heat of water is $c = 4190$ J/kg·K, molar heat capacity $C = (0.0180\ \mathrm{kg/mol})(4190\ \mathrm{J/kg{\cdot}K}) = 75.4\ \mathrm{J/mol{\cdot}K}$

<u>Latent heat</u>

amount of heat needed to convert a unit mass of substance from one state (phase) to another *without* temperature change



latent heat of fusion L_f latent heat of vaporization L_v

$$Q = \pm mL$$

+ absorb heat,
e.g., water → vapor

− release heat,
e.g. vapor → water

unit of L: J/kg

Question
You take a block of ice at 0 °C and add heat to it at a steady rate. It takes a time *t* to completely convert the block of ice to steam at 100 °C. At time *t*/2, you have (all ice at 0 °C / a mixture of ice and water at 0 °C / water at a temperature between 0 °C and 100 °C / a mixture of water and steam at 100 °C)
Answer: see inverted text on P. 588 of textbook

Example 17.8 P. 587
You have $m_w = 0.25$ kg of water initially at $T_w = 25$ °C. How much ice, initially at $T_I = -20$ °C, must you add to obtain a final temperature of $T_f = 0$ °C with all the ice melted?
Principle: total heat change = 0

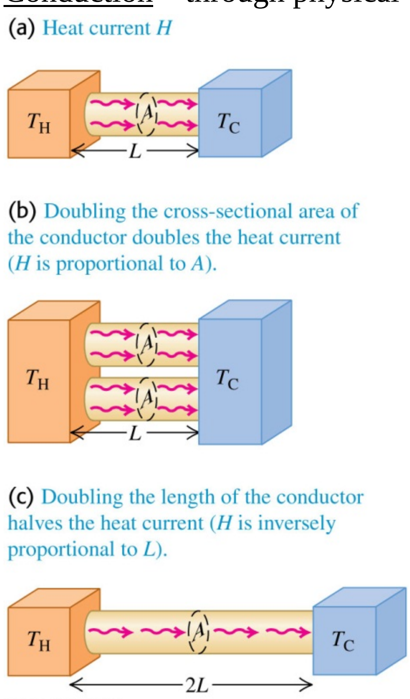
$$\underbrace{m_w c_w (T_f - T_w)}_{\text{heat change of water}} + \underbrace{m_I c_I (T_f - T_I)}_{\text{heat change of ice}} + \underbrace{m_I L_f}_{\text{heat change due to melting of ice}} = 0$$

+ because absorb heat in order to melt

$$m_I = \frac{m_w c_w (T_w - T_f)}{c_I (T_f - T_I) + L_f} = \frac{(0.25\ \text{kg})(4190\ \text{J/kg·K})(25\ \text{K})}{(2100\ \text{J/kg·K})(20\ \text{K}) + (3.34 \times 10^5\ \text{J/kg})} = 0.070\ \text{kg}$$

Mechanisms of Heat Transfer

Conduction – through physical contact



heat current H – rate of heat (energy) flow from high (hot) to low (cold) temperature by conduction

$$H = kA \underbrace{\frac{T_H - T_C}{L}}_{\text{temperature gradient}}$$

thermal conductivity
unit: W/m·K

cross sectional area

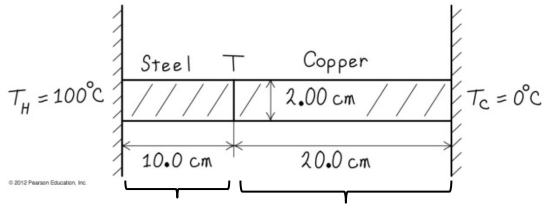
if temperature variation not uniform

$$H = -kA \underbrace{\frac{dT}{dx}}_{\text{temperature gradient}}$$

energy flow in direction of decreasing T

Define **thermal resistance** $R = L/k$, unit: m²·K/W

Example 17.12 P. 591



$$k_S = 50.2\ \text{W/m·K}$$
$$k_{Cu} = 385.0\ \text{W/m·K}$$

$$k_S A \frac{T_H - T}{0.100\ \text{m}} = k_{Cu} A \frac{T - T_C}{0.200\ \text{m}} \quad \Rightarrow \quad T = 20.7\ ℃$$

<u>Convection</u> – through motion of fluid from one region of space to another (such as heating up a pot of water water)

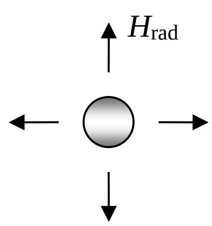
<u>Radiation</u> – through electromagnetic wave, does not need a medium, such as sun → earth
Any body at absolute temperature $T > 0$ radiates energy

Stefan-Boltzmann law $H = Ae\sigma T^4$
where $\sigma = 5.6704 \times 10^{-8}$ W/m²·K⁴ **Stefan-Boltzmann constant**

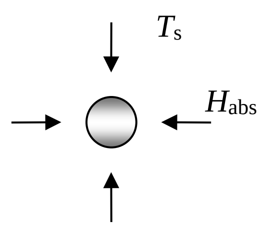
e emissivity (how efficient the body emit/absorb heat, 1 for a perfect emitter/absorber)

A surface area

⚠ Stefan-Boltzmann law holds for both emission and absorption of the same body with the same emissivity e. E.g. a body at temperature T in a surrounding of temperature T_s:



<u>radiation</u> – energy flow from system to environment



<u>absorption</u> – energy flow from environment to system

$$H_{net} = H_{rad} - H_{abs} = Ae\sigma(T^4 - T_s^4)$$

Note:
if $T > T_s$, net emission
if $T < T_s$, net absorption
if $T = T_s$, in thermal equilibrium with surrounding

Example 17.15 P. 594
A human body has temperature 30 °C, surface area 1.20 m², and emissivity close to 1. If the surround temperature is 20 °C , the net rate of energy loss by radiation of the human body is

$$H_{net} = (1.20\ \text{m}^2)(1)(5.67 \times 10^{-8}\ \text{W/m}^2\text{·K}^4)[(303\ \text{K})^4 - (293\ \text{K})^4] = 72\ \text{W}$$

Question
A room has three walls made of concrete, copper and steel respectively, all at the same temperature. Which wall feels coldest to you? Thermal conductivities are 385.0 W/m·K for copper, 50.2 W/m·K for steel, and 0.8 W/m·K for concrete.
Answer: see inverted text on P. 595 of textbook

Clicker Questions:

Q17.1

The illustration shows a thermometer that uses a column of liquid (usually mercury or ethanol) to measure air temperature. In thermal equilibrium, this thermometer measures the temperature of

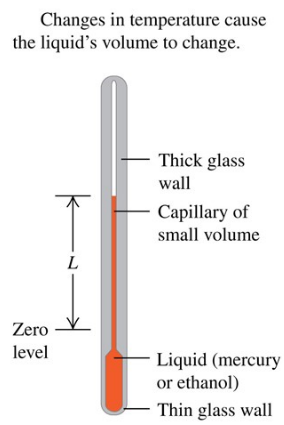
A. the column of liquid.

B. the glass that encloses the liquid.

C. the air outside the thermometer.

D. both A and B.

E. all of A, B, and C.



Q17.2

A sample of a low-density gas is initially at room temperature and has pressure p_0. The gas is warmed at constant volume until the pressure is $2p_0$. Compared to the initial Celsius temperature of the gas, the final Celsius temperature is

A. greater by a factor of more than 2.

B. greater by a factor of 2.

C. greater by a factor between 1 and 2.

D. the same.

E. less.

Q17.6

A pitcher contains 0.50 kg of liquid water at 0°C and 0.50 kg of ice at 0°C. You let heat flow into the pitcher until there is 0.75 kg of liquid water and 0.25 kg of ice. During this process, the temperature of the ice-water mixture

A. increases slightly.

B. decreases slightly.

C. first increases slightly, then decreases slightly.

D. remains the same.

E. The answer depends on the rate at which heat flows.

Q17.8

When you first step out of a swimming pool on a warm day, you feel cool. This is due primarily to

A. conduction.

B. convection.

C. radiation.

D. two of A, B, and C being equally important.

E. all three of A, B, and C being equally important.

Ans: Q17.1) E, Q17.2) A, Q17.6) D, Q17.8) B

Biography from ***Eric Weisstein's World of Science***
http://scienceworld.wolfram.com/biography/

Kelvin, Lord William Thomson (1824-1907)

Scottish mathematician and physicist who contributed to many branches of physics. He was known for his self-confidence, and as an undergraduate at Cambridge he thought himself the sure "Senior Wrangler" (the name given to the student who scored highest on the Cambridge mathematical Tripos exam). After taking the exam he asked his servant, "Oh, just run down to the Senate House, will you, and see who is Second Wrangler." The servant returned and informed him, "*You,* sir!" (Campbell and Higgens, p. 98, 1984). Another example of his hubris is provided by his 1895 statement "heavier-than-air flying machines are impossible" (Australian Institute of Physics), followed by his 1896 statement, "I have not the smallest molecule of faith in aerial navigation other than ballooning...I would not care to be a member of the Aeronautical Society." Kelvin is also known for an address to an assemblage of physicists at the British Association for the advancement of Science in 1900 in which he stated, "There is nothing new to be discovered in physics now. All that remains is more and more precise measurement." A similar statement is attributed to the American physicist Albert Michelson.

Kelvin argued that the key issue in the interpretation of the Second Law of Thermodynamics was the explanation of irreversible processes. He noted that if entropy always increased, the universe would eventually reach a state of uniform temperature and maximum entropy from which it would not be possible to extract any work. He called this the Heat Death of the Universe. With Rankine he proposed a thermodynamical theory based on the primacy of the energy concept, on which he believed all physics should be based. He said the two laws of thermodynamics expressed the indestructibility and dissipation of energy. He also tried to demonstrate that the equipartition theorem was invalid.

Thomson also calculated the age of the earth from its cooling rate and concluded that it was too short to fit with Lyell's theory of gradual geological change or Charles Darwin's theory of the evolution of animals though natural selection. He used the field concept to explain electromagnetic interactions. He speculated that electromagnetic forces were propagated as linear and rotational strains in an elastic solid, producing "vortex atoms" which generated the field. He proposed that these atoms consisted of tiny knotted strings, and the type of knot determined the type of atom. This led Tait to study the properties of knots. Kelvin's theory said ether behaved like an elastic solid when light waves propagated through it. He equated ether with the cellular structure of minute gyrostats. With Tait, Kelvin published *Treatise on Natural Philosophy* (1867), which was important for establishing energy within the structure of the theory of mechanics. (It was later republished under the title *Principles of Mechanics and Dynamics* by Dover Publications).