

IB Physics Topic B1 Thermal Energy Transfers; SL & HL

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Table of Contents

1	The Kelvin Scale	1
2	Phases of Matter	2
3	Temperature and Energy	3
3.1	Internal Energy	3
3.2	Average Kinetic Energy	4
3.3	Specific Heat Capacity	5
3.4	Specific Latent Heat	5
4	Conduction	7
4.1	Thermal Conductivity	7
5	Convection	9
5.1	Sea Breezes	9
5.2	Convection in Earth	10
5.3	Winds	10
5.4	Hot Air Balloons	11
5.5	Minimizing Convection Current	11
6	Thermal Radiation	12
7	Black Body Radiation	13
7.1	The Emission Spectrum	13
7.2	Wien's Displacement Law	15
7.3	Stefan-Boltzmann Law	15
7.4	Observational Astronomy	16
7.5	Apparent Brightness	16

1 The Kelvin Scale

The Kelvin scale is an absolute scale, where 0 K is the lowest possible temperature. The conversion to Celsius is given by

$$T(K) = T(^{\circ}C) + 273$$

E.g., 0 K is -273° C.

2 Phases of Matter

Phase	Shape	Volume	Particular Separation	Compression
Solid	Fixed	Fixed	Very close	Very difficult
Liquid	Not fixed	Fixed	Close	Difficult
Gas	Not fixed	Not fixed; expand to fill the container	Far apart	Easy

Table 1: Comparison of properties of the three phases of matter

Many substances such as water move between the three states depending on the kinetic energy in its molecules.

3 Temperature and Energy

When two objects with different temperatures come in contact, eventually they will reach thermal equilibrium (both at the same temperature).

All objects above 0 K possess some internal kinetic energy in its particles. The higher the temperature, the higher the average kinetic energy of the particles.

3.1 Internal Energy

Internal energy is defined as the sum of KE and potential, as follows

The internal energy of the system is the sum of the total potential energy arising from the intermolecular forces and the total KE of the molecules from Brownian motion.

Notes on the potential energy:

- The stronger the intermolecular attractive forces, the higher the potential energy.
- The larger the separation between particles, also the higher the potential energy.
This should not be confused with the impact of the attractive force — a stronger attraction does not necessarily mean a closer separation.

When energy is supplied to a substance, both components of the internal energy increase:

- The increase in KE causes the particles to vibrate more vigorously, which increases the temperature.
- The increase in potential energy causes the particles to move further apart, sufficiently so for the intermolecular bonds to be broken, decreasing density.

This can then help explain the phase changes of matter.

- During **melting**, the potential energy increases while the KE of the particles remains constant. This means that the temperature during this period of change remains constant, and all the supplied energy is being used to break the bonds between the particles.
- Post-melting, the KE of the particles now increases, which then will increase temperature.
- Molecules gain enough kinetic energy to overcome all intermolecular forces. Molecules break free, becoming a gas. This is **evaporation**.
- Energy transfer goes primarily to potential energy until all bonds are broken.

3.2 Average Kinetic Energy

Planck linked the average translational KE, E_k of a gas molecule to the Kelvin temperature T of the gas

$$E_k = \frac{3}{2}k_B T$$

where $k_B = \frac{\text{gas constant}}{\text{Avogadro's constant}} = \frac{R}{N_A}$ is the Boltzmann constant, $1.381 \times 10^{-23} \text{ J K}^{-1}$.

This constant can be thought of as the conversion factor from temperature to energy. In fact, temperature is a measure of the level of KE of the particles in a substance.

3.3 Specific Heat Capacity

The specific heat capacity of a substance is the amount of energy required to raise the temperature of 1 kg of the substance by 1 K or 1 degree Celsius (the Kelvin scale is more preferable). The equation is

$$Q = mc\Delta T$$

- Q is the energy supplied to the substance in joules.
- m is the mass of the substance in kg.
- c is the specific heat capacity of the substance in $\text{J kg}^{-1} \text{K}^{-1}$.
- ΔT is the change in temperature in K or $^{\circ} \text{C}$.

3.4 Specific Latent Heat

The specific latent heat L for a phase change is the amount of energy Q required to change one kilogram of the substance from one phase to another. In other words,

$$L = \frac{Q}{m} \quad \text{equivalently} \quad Q = mL$$

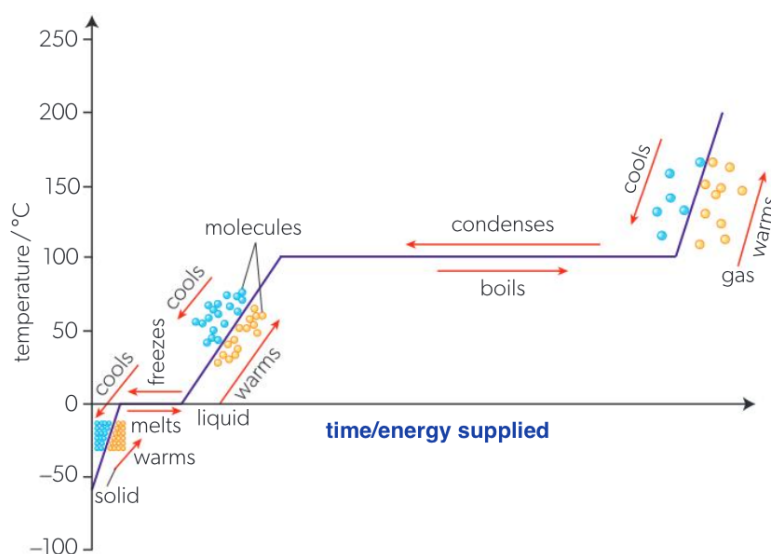


Figure 1: A typical phase change graph

The above graph outlines how the temperature changes during a phase change.

- The graph assumes that the energy is supplied at a constant rate, i.e. energy and time can be used interchangeably as the x -axis.
- The horizontal segments represent the phase change itself, where the temperature remains constant and all the supplied energy is used to break the bonds.
- The sloped lines represent intervals in which the temperature changes without changing the state.
- There are two types of specific latent heat:
 1. **Specific latent heat of fusion** is used for melting and freezing, i.e. phase changes between a solid and a liquid.
 2. **Specific latent heat of vaporization** is used for boiling and condensation, i.e. phase changes between a liquid and a gas.
- The longer horizontal statements indicate a larger specific latent heat, assuming the mass is fixed.

4 Conduction

It is an energy transfer mechanism without bulk movements of particles. There are two mechanisms of conduction:

1. **Lattice vibration** in solids, the energy is transferred by the vibrations of the particles in the lattice. Through this mechanism, the particles in the hotter region transfer kinetic energy to the particles in the cooler region, hence propagating heat through the material.
2. **Free electron movement** in metals, the free electrons carry the energy from the hotter region to the cooler region, by colliding with atoms and electrons to transfer its kinetic energy.

Metals are good conductors of heat due to the presence of **free electrons**; this allows them to propagate heat using both mechanisms. Non-metals are poor conductors due to the lack of free electrons — they cannot propagate heat through free electron movement.

Conduction is much less important in liquids and gases, as the particles are much more spread out. In these states, convection is the primary mode of heat transfer.

4.1 Thermal Conductivity

Thermal conductivity is a measure of how well a thermal conductor can transfer thermal energy through itself in a *steady state* (when the temperature at any point in the object is not changing).

$$\text{conductivity} = \frac{\text{average rate of energy transfer}}{\text{area of material} \times \text{temperature gradient}}$$

$$\frac{\Delta Q}{\Delta t} = \kappa A \times \frac{\Delta T}{\Delta x} \quad \text{or} \quad \kappa = \frac{\Delta Q}{\Delta t} \times \frac{\Delta x}{A \Delta T}$$

where

- κ is the thermal conductivity in $\text{W m}^{-1} \text{K}^{-1}$.
- Q is the energy transferred in joules.
- t is the time taken in seconds.
- A is the cross-sectional area of the material in m^2 , relative to the direction of heat propagation.
- ΔT is the difference in K or $^{\circ} \text{C}$ across the two ends of the material of length Δx .

The idea of thermal conductivity can be used in the design of *double-glazed windows*: The air in between the two glass panels has a poor thermal conductivity — this reduces the rate of heat transfer between the inside and outside of the building.

5 Convection

A heat transfer mechanism through the movement of particles in a fluid. The particles in the hotter region move faster, becoming less dense and rise. The particles in the cooler region are denser thus sink. This creates a convection current, which transfers heat from the hotter region to the cooler region.

5.1 Sea Breezes

During the day, the land has a higher surface temperature than the sea; it heats up the air above it, causing the air to expand (decrease density) and rise, pulling in cooler air from the sea. The inverse happens during the night.

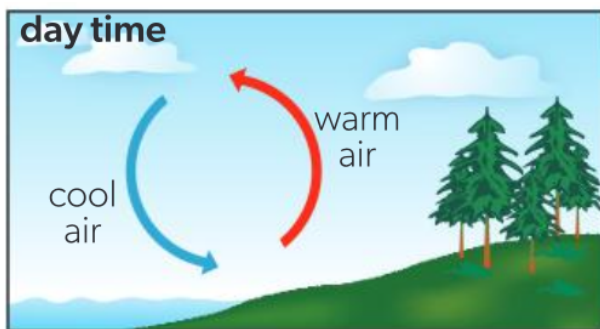


Figure 2: Sea breeze during the day

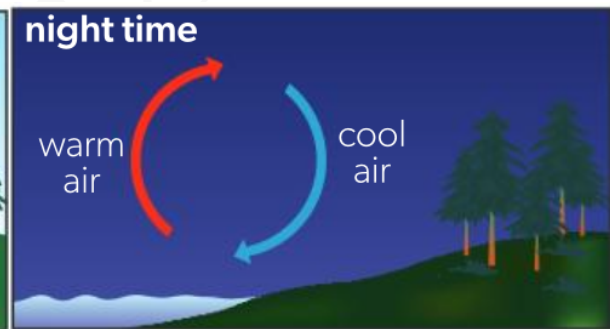


Figure 3: Land breeze during the night

5.2 Convection in Earth

In some parts of the world:

1. The Earth's core is hot and acts as the heat source.
2. The mantle is a fluid, and the heat from the core causes the mantle to rise, creating an upwelling motion.
3. Two currents operate in the same direction and drive the crust upwards, creating new land.

In other parts

1. The convection currents pull the mantle down, creating a subduction zone.
2. This pulls the crust downwards.

5.3 Winds

1. The heating of the Earth's surface by the Sun is uneven.
2. This creates areas that are hotter and areas that are cooler.
3. In hotter areas, the air rises, creating a low-pressure zone.
4. Conversely, in cooler areas, the air sinks, creating a high-pressure zone.
5. Air flows from high- to low-pressure zones, creating winds.
6. The velocity of wind interacts with the Earth's rotation, creating the Coriolis effect.
7. This leads to the rotation of the air masses such that the air circulates in a clockwise direction in the northern hemisphere and anti-clockwise in the southern hemisphere.

5.4 Hot Air Balloons

1. The air in the canopy is heated by a burner.
2. The temperature of the air increase, decreasing its density.
3. This creates a density difference between the hot air in the balloon and the cooler air outside.
4. Due to the pressure difference, the balloon experiences an upthrust.

5.5 Minimizing Convection Current

For instance, covering the liquid surface of a cup of hot drink with a layer of foam reduces the rate of heat loss.

1. Conduction is reduced; foam traps air, which is a poor conductor.
2. Convection current is reduced; the upper surface of the foam is cooler, and this reduces the temperature difference with the surrounding air, thus, minimizing the convection current.

6 Thermal Radiation

This is the transfer of thermal energy through electromagnetic radiation. This means that the transfer does not require a medium, and can occur in a vacuum. The energy is transferred in the form of photons, which are massless particles that travel at the speed of light.

When ions accelerate, they emit electromagnetic radiation. This is the basis of thermal radiation.

Matt black surfaces are good emitters and absorbers of radiation, while shiny surfaces are poor absorbers and emitters but good reflectors.

7 Black Body Radiation

A **black body** is a perfect emitter and absorber of radiation that absorbs E.M. radiation of all wavelengths that are incident on it. This is an idealized concept that cannot be realized in practice. However, a good approximation is a small hole in a cavity, where the radiation is absorbed and re-emitted multiple times, thus approximating a black body.

- **Perfect absorption:** When radiation enters the small hole, it has very little chance of escaping. The radiation bounces around inside the cavity, reflecting multiple times off the walls. With each reflection, some of the energy is absorbed by the cavity walls. Eventually, nearly all the incident radiation will be absorbed.

The following are true for the emission of radiation from the cavity:

1. The intensity of radiation is independent of the material from which the cavity is made.
2. The intensity increases with increasing temperature.

7.1 The Emission Spectrum

Light consists of different wavelengths, and the intensity of radiation emitted at different wavelengths is called the emission spectrum. This can be measured by a spectrometer.

A spectrometer measures the intensity of radiation emitted for each of the different wavelengths that the radiation encapsulates.

Intensity, in W m^{-2} , is given as the power emitted per unit area

$$I = \frac{P}{A}$$

The following graph is one obtained from the spectrometer:

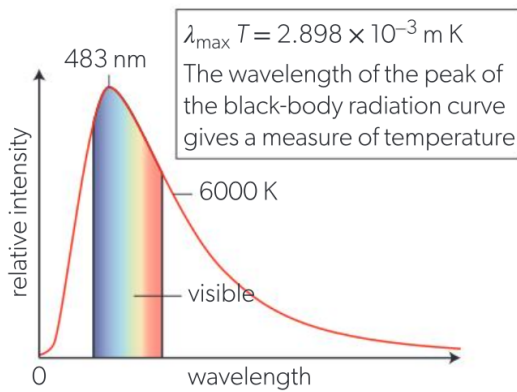


Figure 4: Sun's spectrum, assuming it's a black-body

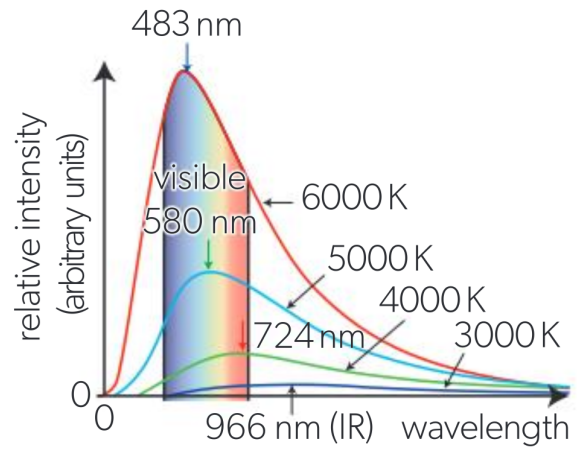


Figure 5: Black-body spectra for other temperatures

Figure 4 shows the following

- There is a peak value at around 500 nm
- The intensity is greater in the visible region than in the invisible region.
- Towards the positive infinity direction on the x -axis, the intensity decreases, infinitely tending to zero.

The family of curves in Figure 5 shows that, as temperature increases

- the overall intensity of radiation increases
- the curves skew towards shorter wavelengths; the peaks translate towards the origin.

7.2 Wien's Displacement Law

This states that the wavelength at which the intensity of radiation is maximum λ_{\max} is related to the absolute temperature of the black body T by

$$\lambda_{\max}T = b$$

where b is Wien's displacement constant, $2.9 \times 10^{-3}\text{m K}$. This should not be confused with the apparent brightness of an object.

This equation allows us to predict the peak wavelength of the radiation emitted by a black body at a given temperature.

7.3 Stefan-Boltzmann Law

This states that the total power (total energy radiated per second), equivalently, the luminosity L emitted by a black body is given by

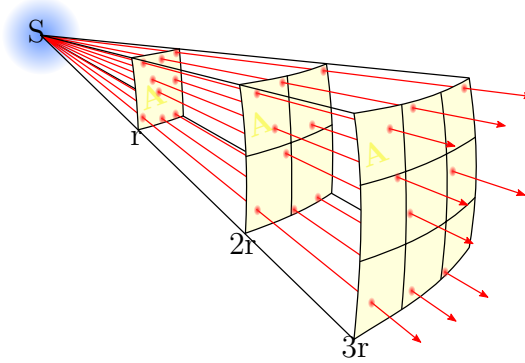
$$P \equiv L = \sigma AT^4$$

- A is the total surface area of the black body.
- σ is the Stefan-Boltzmann constant, $5.67 \times 10^{-8}\text{W m}^{-2}\text{K}^{-4}$.
- T is the temperature of the black body in K.

Note that this equation is often combined with [Equation \(2\)](#).

Also note that the Stefan-Boltzmann law **only considers heat transfer by radiation** and thus does not account for conduction or convection. Hence, the realistic rate of transfer is higher than the calculated value, as convection and conduction also take place.

7.4 Observational Astronomy



The intensity I of radiation decreases with distance d from the source and it obeys the inverse square law. The following provides an intuitive explanation:

- At $d = 1$, the intensity is I , and the total energy is distributed over an area of A .
- At $d = 2$, the area over which the energy is distributed is $4A$ (by considering scale factors). However, the total energy is the same, but now it is distributed over four times the original, which means that the energy per unit area is $\frac{1}{4}$ of the original.

Formally, the relationship is given by

$$I = \frac{P}{4\pi d^2} \quad (1)$$

where P is the total power emitted by the source and I is measured in W m^{-2}

7.5 Apparent Brightness

The apparent brightness b of a star is just the intensity of radiation received from the star at the Earth's surface. This is given by the following, which is analogous to [Equation \(1\)](#)

$$b = \frac{L}{4\pi d^2} \quad (2)$$

where $L \equiv P$ is the luminosity of the star, and d is the star-Earth distance.