HL IB Physics

Thermal Energy Transfers

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Solids, Liquids & Gases

Solids, Liquids & Gases

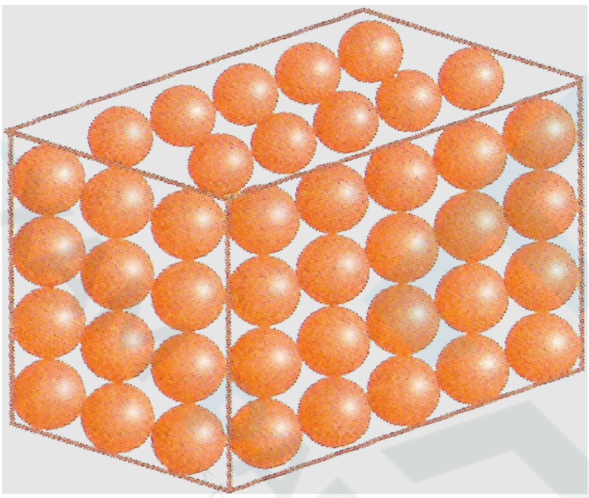
- The three states of matter are **solid**, **liquid** and **gas**
- The **kinetic theory of matter** is a model that attempts to explain the properties of the three states of matter

Solids

- Particles in a solid...

- Are **closely packed**
- Are arranged in a fixed pattern (**lattice structure**)
- Can only **vibrate** about their fixed positions
- Have **low energies** compared to particles in liquids and gases
- Therefore, do **not** have enough energy to **overcome** the **intermolecular forces** of attraction holding them together

Molecular arrangement in a solid



In a solid, particles are arranged in a fixed pattern, with no spaces between them, and are only able to vibrate about their fixed positions

- As a result of the arrangement and behaviour of their particles, solids...
  - Have a fixed shape (although some solids can be deformed when forces are applied)
  - Have a fixed volume
  - Are very difficult to compress
  - Have higher densities than liquids and gases

Liquids

- Particles in a liquid...
  - Are **closely packed**
  - Are **randomly** arranged (i.e. there is no fixed pattern)
  - Can **flow** past each other
  - Have **higher energies** than particles in solids, but lower energies than gas particles
  - Therefore, have enough energy to **partially overcome** the **intermolecular forces** of attraction holding them together

- As a result of the arrangement and behaviour of their particles, liquids...
  - Do not have a fixed shape and take the shape of the container they are held in
  - Have a fixed volume
  - Are difficult to compress
  - Have lower densities than solids, but higher densities than gases

Gases

- Particles in a gas...
  - Are **far apart** (the average distance between the particles is ~10 times greater than the distance between the particles in solids and liquids)
  - Are **randomly** arranged
  - Move around in **all directions** at a variety of speeds, occasionally **colliding** with each other and with the walls of the container they are in
  - Are negligible in size compared to the volume occupied by the gas
  - Have **higher energies** than particles in solids and liquids
  - Therefore, have enough energy to overcome the **intermolecular forces** of attraction holding them together

Molecular arrangement in a gas

- As a result of the arrangement and behaviour of their particles, gases...
  - Do not have a fixed shape and take the shape of the container they are held in
  - Do not have a fixed volume and expand to completely fill the available volume
  - Can be compressed
  - Have the lowest densities (~1000 times smaller than the densities of solids and liquids)

State of Matter	Solid	Liquid	Gas
Particle arrangement	Fixed pattern (lattice structure)	Random	Random
Space between particles	No space	Some space	Large space
Particle movement	Vibrates around a fixed position	Flows past each other	Moves around at different speeds
Particle energy	Low	Medium	High
Substance shape	Fixed	Not fixed	Not fixed
Substance volume	Fixed	Fixed	Not fixed

Density

Density

- Density is the **mass per unit volume** of an object
  - If two objects occupy the same volume, the object with a lower density will have a lower mass
  - For example, a bucket filled with feathers will have a lower mass than the same bucket filled with sand, because feathers have a lower density than sand
- The units of density depend on the units used for mass and volume:
  - If the mass is measured in *g* and volume in **cm^3**, then the density will be in **g / cm^3**
  - If the mass is measured in *kg* and volume in **m^3**, then the density will be in **kg / m^3**
- The volume of an object may not always be given directly but can be calculated using the appropriate formula

Temperature Scales

Temperature Scales

- On the thermodynamic (Kelvin) temperature scale, **absolute zero** refers to the lowest possible temperature
  - This is equal to 0 K or –273 °C
- It is not possible to have a temperature lower than 0 K
  - This means a temperature in Kelvin will **never** be a negative value

- Absolute zero is defined as:

The temperature at which the molecules in a substance have zero kinetic energy

- This means for a system at 0 K, it is not possible to remove any more energy from it
- Even in space, the temperature is roughly 2.7 K, just above absolute zero

How to use the Kelvin Scale

- To convert between temperatures *θ* in the Celsius scale, and *T* in the Kelvin scale, use the following conversion:

$$\theta \,/\, °C = T \,/\, K - 273$$

$$T \,/\, K = \theta \,/\, °C + 273$$

Worked example

In many ideal gas problems, room temperature is considered to be 300 K.

What is this temperature in degrees Celsius?

Answer:

Step 1: Recall the Kelvin to Celsius conversion

$$\theta / °C = T / K - 273$$

Step 2: Substitute in the value of 300 K

$$300 \text{ K} - 273 = 27 \text{ °C}$$

Temperature & Kinetic Energy

Temperature & Kinetic Energy

- Particles in gases usually have a range of speeds
- The average kinetic energy of the particles E_k can be calculated using the equation

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

- Where:
  - E_k = average kinetic energy of the particles in joules (J)
  - $k_B = 1.38 \times 10^{-23}$ J K^{-1} (Boltzmann's constant)
  - T = absolute temperature in kelvin (K)
- This tells us that the absolute temperature of a body is **directly proportional** to the average kinetic energy of the molecules within the body

Worked example

The surface temperature of the Sun is 5800 K and contains mainly hydrogen atoms.

Calculate the average speed of the hydrogen atoms, in km s^{-1}, near the surface of the Sun.

Answer:

Step 1: List the known quantities

- Temperature, T = 5800 K
- Mass of a hydrogen atom = mass of a proton, m_p = 1.673 × 10^{-27} kg
- Boltzmann constant, k_B = 1.38 × 10^{-23} J K^{-1}

Step 2: Equate the equations relating kinetic energy with temperature and speed

- Average kinetic energy of a molecule: $E_k = \frac{3}{2}k_BT$
- Kinetic energy: $E_k = \frac{1}{2}mv^2$

$$\frac{3}{2}k_BT = \frac{1}{2}m_pv^2$$

Step 3: Rearrange for average speed and calculate

$$\frac{3k_BT}{m_p} = v^2$$

$$v = \sqrt{\frac{3k_BT}{m_p}} = \sqrt{\frac{3 \times (1.38 \times 10^{-23}) \times 5800}{1.673 \times 10^{-27}}}$$

Average speed: v = 11 980 m s^{-1} = 12 km s^{-1}

Internal Energy

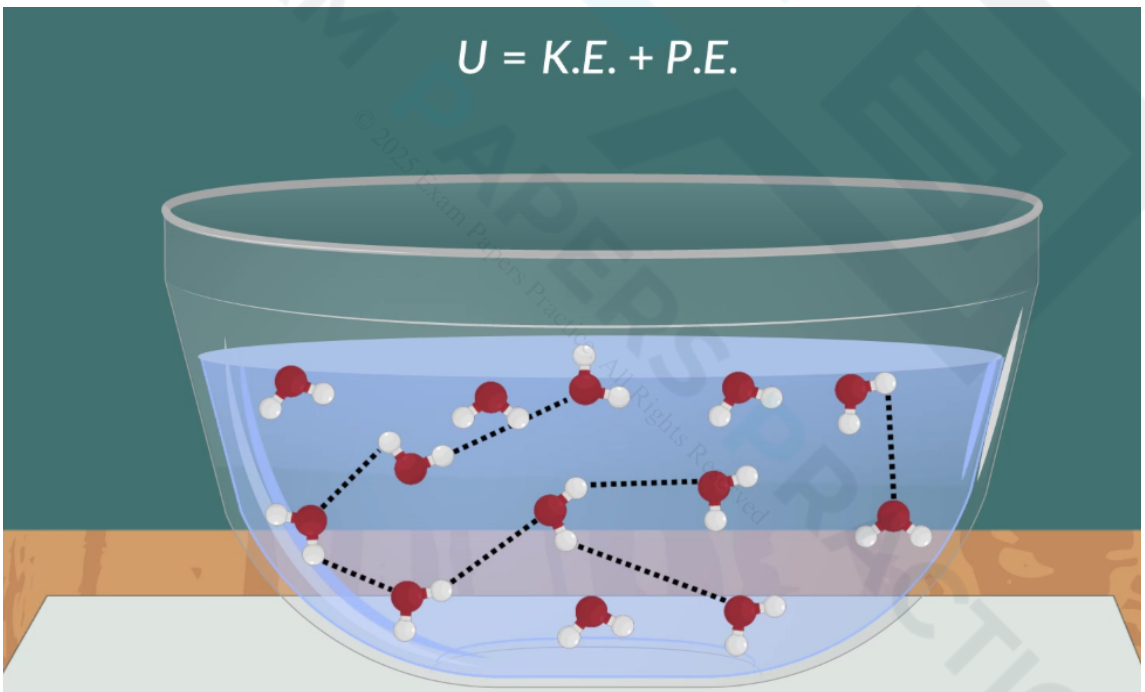
Internal Energy

- When a substance gains or loses thermal energy, its **internal energy** increases or decreases
- The internal energy of a substance is defined as:

  The sum of the total kinetic energy and the total intermolecular potential energy of the particles within the substance

- As thermal energy is transferred to a substance, two things can happen:
  - An increase in the average kinetic energy of the molecules within the substance - i.e. the molecules vibrate and move at higher speeds
  - An increase in the potential energy of the molecules within the substance - i.e. the particles get further away from each other or move closer to each other

What is internal energy?



Kinetic energy and potential energy are the two energy stores that make up internal energy

- Temperature is a measure of the average kinetic energy of the molecules
  - Therefore, only an **increase** in the average kinetic energy of the molecules will result in an **increase in temperature** of the substance

- Due to thermal expansion, when the temperature of a substance increases, the **potential energy** of the molecules also increases
- When **only** the **potential energy** of the molecules changes, the **temperature** of the substance **does not change**
  - This is the case for all **state changes** (e.g. melting, boiling)

Thermal Equilibrium

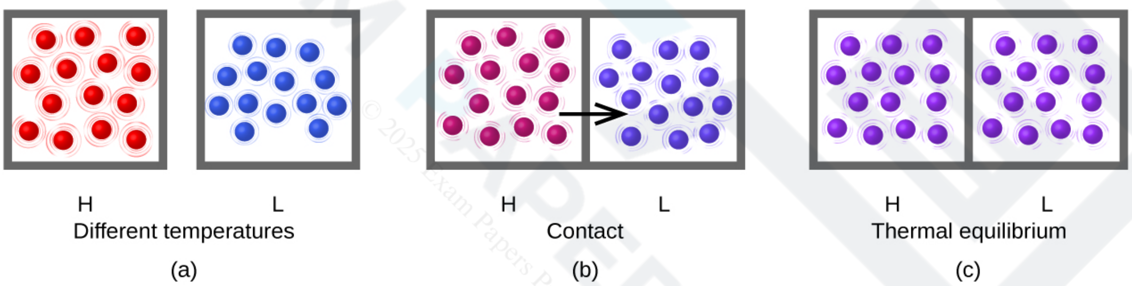
Thermal Equilibrium

- Thermal energy is **always** transferred from a hotter region to a lower region
  - Eventually, once the regions reach the same temperature, no more thermal energy is transferred
- Thermal equilibrium is defined as:

  When two substances in contact with each other no longer exchange any heat energy and both reach an equal temperature

- There is no longer thermal energy transfer between the regions

Thermal equilibrium and the direction of energy flow



Two regions of different temperatures will eventually reach thermal equilibrium

- The two regions need to be in **thermal contact** for this to occur
  - The **hotter** region will cool down and the **cooler** region will heat up until they reach the **same** temperature
- An example of this is ice in room temperature water
  - The ice cubes heat up as thermal energy is transferred **from** the water
  - Therefore, the water cools down as thermal energy is transferred away from the water **to** the ice

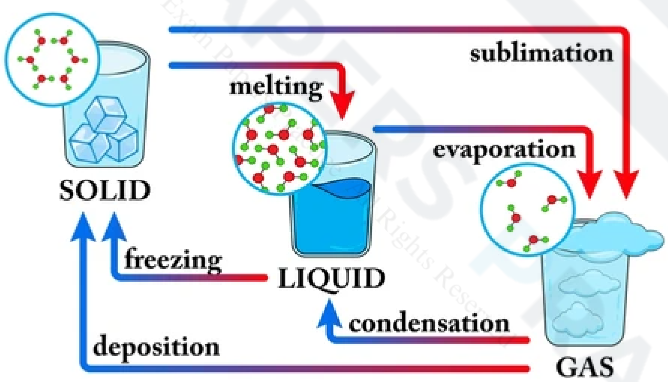
Changes of State

Changes of State

- A **change of state,** or **phase** change, happens whenever matter changes from one phase (solid, liquid or gas) into another
  - During a phase change, thermal energy is transferred to or from a substance

- This energy transfer does **not change the temperature** of the substance undergoing the phase change, meaning
  - The thermal energy provided (or removed) does not affect the kinetic energy of the molecules within the substance
  - Only the potential energy (i.e. the spacing between the atoms or molecules) is affected
- The four main phase changes are:
  - **Melting** - i.e. when a substance changes from solid to liquid as it absorbs thermal energy
  - **Freezing** - i.e. when a substance changes from liquid to solid as it releases thermal energy
  - **Vaporisation** (or **boiling**) - i.e. when a substance changes from liquid to gas as it absorbs thermal energy
  - **Condensation** - i.e. when a substance changes from gas to liquid as it releases thermal energy

Phase changes of water



- Each substance has its own melting (or freezing) and boiling points
  - For example, the freezing point of water is 0 °C and its boiling point is 100 °C
- Possible phase changes of water include:
  - Solid ice **melting** into liquid water at 0 °C
  - Liquid water **boiling** and changing into gaseous water vapour at 100 °C
- Both these changes happen when **thermal energy** is absorbed
  - If thermal energy is released from water vapour at 100 °C, it condenses back into water
  - If water continues to release thermal energy, it cools down until it reaches 0 °C and **freezes** into ice
- Melting and freezing happen at the **melting / freezing point** of a substance
- Vaporisation and condensation happen at the **boiling point** of a substance

Specific Heat Capacity

Specific Heat Capacity

- The amount of thermal energy needed to change the temperature of an object depends on:
  - The **change in temperature** required ΔT, i.e. the larger the change in temperature the more energy is needed
  - The **mass** of the object *m*, i.e. the greater the mass the more energy is needed
  - The **specific heat capacity** c of the given substance, i.e. the higher the specific heat capacity the more energy is needed

Substance	Specific Heat Capacity ($J\ kg^{-1}\ K^{-1}$)
Water	4200
Ice	2200
Aluminium	900
Copper	390
Gold	130

- The equation for the thermal energy transferred, Q, is then given by

$$Q = mc\Delta T$$

- Where:
  - *m* = mass of the substance (kg)
  - ΔT = change in temperature (K or °C)
  - c = specific heat capacity of the substance ($J\ kg^{-1}\ K^{-1}$)
- The specific heat capacity of a substance is defined as:

  The amount of energy required to change the temperature of 1 kg of a substance by 1 K (or 1°C)

- This definition can be explained when the above equation is rearranged for c:

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

- This means the **higher** the specific heat capacity of a substance, the **longer** it takes for the substance to warm up or cool down
  - Note that the specific heat capacity is measured in J kg K

Worked example

A piece of copper of mass 50 g is heated until it reaches a temperature of 120 °C. The copper is removed from the heat and immediately placed into 250 mL of water at 25 °C.

The temperature of the water and copper is measured until they reach thermal equilibrium.

Determine the final temperature of the copper and water, in degrees Celsius (°C), assuming no heat is lost to the surroundings.

- The specific heat capacity of water is 4200 J kg^{-1} K^{-1}
- The specific heat capacity of copper is 390 J kg^{-1} K^{-1}

Answer:

Step 1: Write down the known quantities

- Mass of copper, m_c = 50 g = 0.05 kg
- Mass of water, m_w = 250 ml = 0.25 kg (since 1 litre = 1 kg)
- Initial temperature of copper, T_c = 120 °C
- Initial temperature of water, T_w = 25°C
- Specific heat capacity of water, c_w = 4200 J kg^{-1} K^{-1}
- Specific heat capacity of copper, c_c = 390 J kg^{-1} K^{-1}

Step 2: Write down the equation for thermal energy

$$Q = mc\Delta T$$

Step 3: Equate the equations for the energy transferred from the copper to the water

- The copper is at a higher initial temperature than the water, hence thermal energy will be transferred from the copper to the water
- The energy lost by the copper = the energy gained by the water

$$-Q_c = Q_w$$

$$-m_c c_c \Delta T_c = m_w c_w \Delta T_w$$

Step 4: Determine the final temperature T_f of the copper and water

- Since the water and copper reach thermal equilibrium, their final temperature T_f will be **the same**

$$-m_c c_c (T_f - 120) = m_w c_w (T_f - 25)$$

$$-0.05 \times 390 \times (T_f - 120) = 0.25 \times 4200 \times (T_f - 25)$$

$$2340 - 19.5 T_f = 1050 T_f - 26\,250$$

$$1069.5\ T_f = 28\,590$$

$$T_f = \frac{28\,590}{1069.5} = 26.7\ °C$$

Specific Latent Heat

Specific Latent Heat

- During a **phase change** (i.e. a change of state) thermal energy is transferred to a substance or removed from it
  - During a phase change, the **temperature** of the substance **does not change**
- In this case, the thermal energy is calculated as follows:

$$Q = mL$$

- Where:
  - Q = heat energy transferred (J)
  - m = mass of the substance in kilograms (kg)
  - L = specific latent heat of the substance (J kg^{-1})
- The specific latent heat of a substance is defined as:

  The amount of energy required to change the state of 1 kg of a substance without changing its temperature

- This definition can be explained when the above equation is rearranged for L:

$$L = \frac{Q}{m}$$

- This means that the higher the specific latent heat of a substance, the greater the energy needed to change its state
  - Note that the specific latent heat is measured in J kg^{-1}
- The amount of energy required to melt (or solidify) a substance is **not** the same as the amount of energy required to evaporate (or condense) the same substance
- Hence, there are two types of specific heat:
  - **Specific latent heat of fusion, L_f**
  - **Specific latent heat of vaporisation, L_v**

Specific Latent Heat of Fusion

- Specific latent heat of **fusion** is defined as:

  The energy released when 1 kg of liquid freezes to become solid at constant temperature
  OR
  The energy absorbed when 1 kg of solid melts to become liquid at constant temperature

- This is because fusion applies to the following phase changes:
  - Solid to liquid
  - Liquid to solid

Specific Latent Heat of Vaporisation

- Specific latent heat of **vaporisation** is defined as:

The energy released when 1 kg of gas condenses to become liquid at constant temperature
OR
The energy absorbed when 1 kg of liquid evaporates to become gas at constant temperature

- This is because vaporisation applies to the following phase changes:
  - Liquid to gas
  - Gas to liquid

What is the difference between the latent heat of vaporisation and fusion?

- For a given substance, the value of the specific latent heat of vaporisation is always **higher** than the value of the specific latent heat of fusion
  - In other words, $L_v > L_f$
- This means more energy is required to **evaporate** (or condense) a substance than is needed to **melt** it (or solidify it)
- During melting (**fusion**):
  - The intermolecular forces of attraction only need to be partially overcome to turn from a solid to a liquid
- During evaporation (**vaporisation**):
  - The intermolecular forces of attraction need to be completely overcome to turn from liquid to gas
  - This requires a lot more energy

Substance	Specific Latent Heat of Fusion ($J\ kg^{-1}$)	Specific Latent Heat of Vaporisation ($J\ kg^{-1}$)
Water	4.0×10^5	1.1×10^7
Aluminium	3.3×10^5	2.3×10^6
Copper	2.1×10^5	4.7×10^6
Gold	6.3×10^4	1.7×10^6

Worked example

Determine the energy needed to melt 200 g of ice at 0°C.

- The specific latent heat of fusion of water is 3.3×10^5 J kg^{-1}
- The specific latent heat of vaporisation of water is 2.3×10^6 J kg^{-1}

Answer:

Step 1: Determine whether to use latent heat of fusion or vaporisation

- We need to use the specific latent heat of **fusion** because the phase change occurring is from **solid** to **liquid**

Step 2: List the known quantities

- Mass of the ice, m = 200 g = 0.2 kg
- Specific latent heat of fusion of water, $L_f = 3.3 \times 10^5$ J kg^{-1}

Step 3: Write down the equation for the latent heat of fusion

$$Q = mL_f$$

Step 4: Substitute numbers into the equation

$$Q = 0.2 \times (3.3 \times 10^5)$$

$$Q = 66\,000 = 66 \text{ kJ}$$

Worked example

Energy is supplied to a heater at a rate of 2500 W.

Determine the time taken, in minutes, to boil 500 ml of water at 100°C. Ignore energy losses.

- The specific latent heat of fusion of water is 3.3×10^5 J kg^{-1}
- The specific latent heat of vaporisation of water is 2.3×10^6 J kg^{-1}

Answer:

Step 1: Determine whether to use latent heat of fusion or vaporisation

- We need to use the specific latent heat of **vaporisation** because the phase change occurring is from **liquid** to **gas**

Step 2: Write down the known quantities

- Power, P = 2500 W
- Mass, m = 500 ml = 0.5 kg (since1 litre = 1 kg)
- Specific latent heat of vaporisation of water, $L_V = 2.3 \times 10^6$ J kg^{-1}

Step 3: Recall the equations for power and latent heat of

- Power: $P = \frac{E}{t} \Rightarrow E = Pt$
- Thermal energy: $Q = mL_V$

Step 4: Equate the two expressions for energy

$$Pt = mL_V$$

Step 5: Rearrange for the time *t* and substitute in the values

$$t = \frac{mL_V}{P}$$

$$t = \frac{0.5 \times (2.3 \times 10^6)}{2500}$$

t = 460 s = 7.7 min

Heating & Cooling Curves

- A **heating** or **cooling curve** shows how the temperature of a substance changes with time
- The two main features of these curves are
  - The flat sections
  - The non-flat sections
- The flat sections show...
  - No **change in temperature** over time
  - The substance is undergoing a **phase change**
  - The thermal energy supplied to or removed from the substance only affects the **potential energy of the particles**
- The non-flat sections show...
  - **Changes in temperature** over time
  - The substance is **heating up** or **cooling down**
  - That the thermal energy supplied to or removed from the substance changes the **average kinetic energy of the particles**, hence resulting in an overall change in the temperature of the substance

Heating Curves

- When energy is supplied to a **solid**, its temperature will increase until it reaches its **melting point**
  - Once at the melting point, the temperature remains **constant** until the substance has **melted** completely
- If energy continues to be supplied, the temperature of the **liquid** will increase until it reaches its **boiling point**
  - Once at the boiling point, the temperature remains **constant** until the substance has **vaporised** completely

Cooling Curves

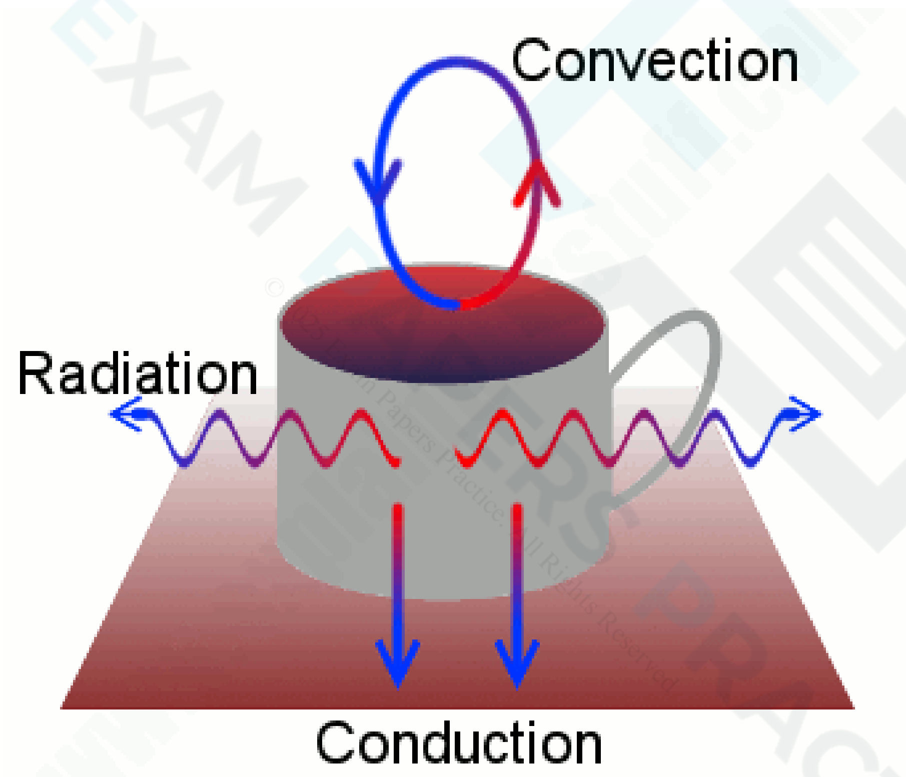
- When energy is removed from a **gas**, its temperature will decrease until it reaches its **boiling point**
  - Once at the boiling point, the temperature remains **constant** until the substance has **condensed** completely
- If energy continues to be removed, the temperature of the **liquid** will decrease until it reaches its **freezing point**
  - Once at the freezing point, the temperature remains **constant** until the substance has **frozen** completely
- Heating or cooling curves can also display how the temperature of a substance changes with energy
  - In the following worked example, **energy** (in J) is plotted on the **x-axis** instead of time

Thermal Conduction

Thermal Conduction

- Thermal energy can be transferred from a hotter area to a cooler area through one of the following mechanisms:
  - Conduction
  - Convection
  - Radiation

Thermal conduction, convection and radiation in a mug of tea



- Objects will **always** lose heat until they are in thermal equilibrium with their surroundings
  - For example, a mug of hot tea will cool down until it reaches room temperature

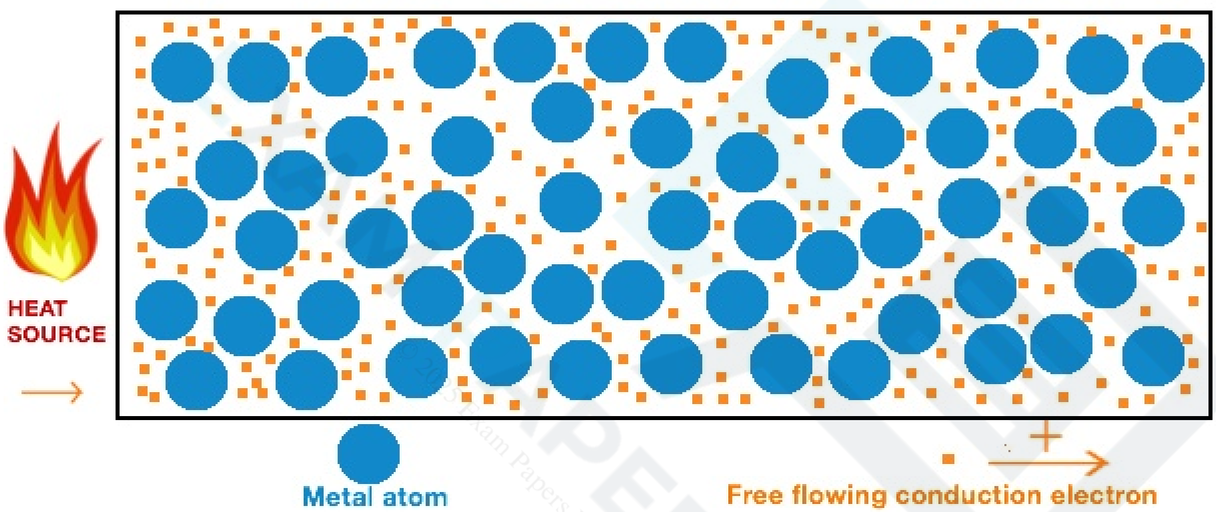
Conduction

- Conduction is the main method of thermal energy transfer in **solids**
- Conduction occurs when:

Two solids of different temperatures come in contact with one another, thermal energy is transferred from the hotter object to the cooler object

- Metals are the best thermal **conductors**
  - This is because they have a high number of **free electrons**
- Non-metals, such as plastic or glass, are poor at conducting heat
  - Poor conductors of heat tend to also be poor conductors of electricity
  - This suggests a link between the mechanisms behind both types of conduction
- Liquids and gases are even poorer thermal conductors
  - This is because the atoms are **further apart**

Conduction of Heat in a Metal



During conduction, the atoms in a solid vibrate and collide with each other

- Conduction can occur through two mechanisms:
  - Atomic vibrations
  - Free electron collisions
- When a substance is heated, the atoms, or ions, start to move around, or **vibrate**, more
  - The atoms at the hotter end of the solid will vibrate more than the atoms at the cooler end
  - As they do so, they **bump into each other**, transferring energy from atom to atom
  - These collisions transfer internal energy until **thermal equilibrium** is achieved throughout the substance
  - This occurs in **all solids**, metals and non-metals alike
- Metals are especially good at conducting heat due to their high number of **delocalised electrons**
  - These can collide with the atoms, increasing the rate of transfer of **vibrations** through the material
  - This allows metals to achieve thermal equilibrium **faster** than non-metals

Worked example

Determine which of the following metals is likely to be the best thermal conductor, and which is likely to be the worst.

Metal	Density / g cm^{-3}	Relative atomic mass
Copper	8.96	63.55
Steel	7.85	55.85
Aluminium	2.71	26.98

Assume that each metal contributes one free electron per atom.

Answer:

Step 1: Use dimensional analysis to determine the equation for the number of free electrons

- Units for number of free electrons per cubic centimetre, [n] = cm^{-3}
- Units for density, [ρ] = g cm^{-3}
- Units for Avogadro's number, [N_A] = mol^{-1}
- Units for relative atomic mass, [A] = g mol^{-1}

$$[n]^a = [\rho]^b [N_A]^c [A]^d$$

$$(cm^{-3})^a = (g\ cm^{-3})^b (mol^{-1})^c (g\ mol^{-1})^d$$

- The only unit present on both sides is cm^{-3}, therefore:

$$a = b = 1$$

- No other units are present on both sides, so:

$$c + d = 0$$

$$b + d = 0$$

$$\therefore d = -1, c = 1$$

Step 2: Write out the equation for the number of free electrons per cubic centimetre

$$[n]^1 = [\rho]^1 [N_A]^1 [A]^{-1}$$

$$n = \frac{\rho N_A}{A}$$

Step 3: Calculate the number of free electrons in each metal

- Avogadro constant, $N_A = 6.02 \times 10^{23}$ mol^{-1} (this is given in the data booklet)

Copper: $$n = \frac{8.96 \times (6.02 \times 10^{23})}{63.55} = 8.49 \times 10^{22} \text{ cm}^{-3}$$

Steel: $$n = \frac{7.85 \times (6.02 \times 10^{23})}{55.85} = 8.46 \times 10^{22} \text{ cm}^{-3}$$

Aluminium: $$n = \frac{2.71 \times (6.02 \times 10^{23})}{26.98} = 6.05 \times 10^{22} \text{ cm}^{-3}$$

Step 4: Rank the metals from best thermal conductor to worst

- Best thermal conductor = **copper** (highest number of free electrons)
- Worst thermal conductor = **aluminium** (lowest number of free electrons)

Temperature Gradient Equation

Thermal Conductivity

- The conductivity of a material can be quantified by its **thermal conductivity**
- Thermal conductivity is defined as

The ability of a substance to transfer heat via conduction

- It is denoted by the symbol *k* and has units of $W\ m^{-1}\ K^{-1}$
- The thermal conductivities of some common materials are shown in the table below

Substance	Thermal conductivity / $W\ m^{-1}\ K^{-1}$
air	0.024
rubber	0.13
water	0.6
ice	1.6
iron	80
copper	400
silver	429
diamond	1600

- Excellent thermal **conductors**...
  - Have **high** values of thermal conductivity
  - Transfer thermal energy at a **fast** rate
  - (Usually) contain a **large** number of delocalised electrons (diamond being the obvious exception)
- Poor thermal conductors (**insulators**)...
  - Have **low** values of thermal conductivity
  - Transfer thermal energy at a **slow** rate
  - Contain **few** delocalised electrons

Temperature Gradient Formula

- When there is a temperature **difference** between two points, thermal energy will flow from the region of **higher** temperature to the region of **lower** temperature
  - This is known as a **temperature gradient**
- The **rate** of the **heat transfer** via conduction is given by

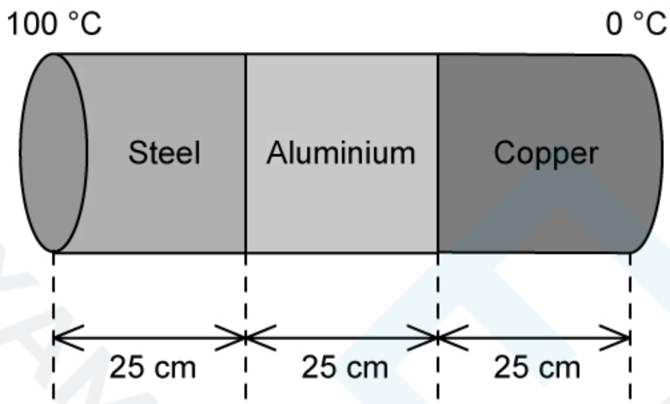
$$\frac{\Delta Q}{\Delta t} = kA\frac{\Delta T}{\Delta x}$$

- Where
  - $\frac{\Delta Q}{\Delta t}$ = flow of thermal energy per second (W)
  - k = thermal conductivity of the material (W m^{-1} K^{-1})
  - A = cross-sectional area (m^2)
  - ΔT = temperature difference (K or °C)
  - Δx = thickness of the material (m)
- The flow of thermal energy per second can be considered to be **uniform** across a temperature gradient, provided A is constant, regardless of material
  - This is analogous to electrical current being constant throughout a series circuit, even though the components may have different resistances

Conduction of thermal energy through a solid

Worked example

A composite rod is made of three rods; steel, aluminium and copper. Each rod has the same length and cross-section, as shown in the diagram.



The steel end is held at 100°C and the copper end is held at 0°C.

Determine the temperatures at the steel-aluminium junction and the aluminium-copper junction.

Assume that the rods are perfectly insulated from the surroundings.

- Thermal conductivity of steel = 60 W m^{-1} K^{-1}
- Thermal conductivity of aluminium = 240 W m^{-1} K^{-1}
- Thermal conductivity of copper = 400 W m^{-1} K^{-1}

Answer:

Step 1: Analyse the scenario and set up an equation

- As the rods have identical dimensions, the amount of heat flowing through each rod per second is uniform and must be the same
- Therefore, rate of energy transfer in steel = rate of energy transfer in aluminium

$$\frac{\Delta Q_s}{\Delta t} = \frac{\Delta Q_a}{\Delta t} = \frac{\Delta Q_c}{\Delta t}$$

$$k_s A \frac{\Delta T_s}{\Delta x} = k_a A \frac{\Delta T_a}{\Delta x} = k_c A \frac{\Delta T_c}{\Delta x}$$

$$k_s \Delta T_s = k_a \Delta T_a = k_c \Delta T_c$$

Step 2: Form two simultaneous equations and substitute in the values of Δ*T* and *k*

- Temperature difference in steel: $\Delta T_s = (100 - T_1)$
- Temperature difference in aluminium: $\Delta T_a = (T_1 - T_2)$
- Temperature difference in copper: $\Delta T_c = (T_2 - 0)$

$$k_s(100 - T_1) = k_a(T_1 - T_2) \quad \Rightarrow \quad 60(100 - T_1) = 240(T_1 - T_2) \text{ eq. (1)}$$

$$k_a(T_1 - T_2) = k_c(T_2 - 0) \quad \Rightarrow \quad 240(T_1 - T_2) = 400(T_2 - 0) \text{ eq. (2)}$$

Step 3: Expand and simplify eq. (1)

$$6000 - 60T_1 = 240T_1 - 240T_2$$

$$300T_1 - 240T_2 = 6000$$

$$5T_1 - 4T_2 = 100$$

Step 4: Expand and simplify eq. (2)

$$240T_1 - 240T_2 = 400T_2$$

$$240T_1 = 640T_2$$

$$T_2 = \frac{3}{8}T_1$$

Step 5: Determine the temperature at the steel-aluminium junction T_1

$$5T_1 - 4\left(\frac{3}{8}T_1\right) = 100$$

$$\frac{7}{2}T_1 = 100$$

$$T_1 = \frac{200}{7} = 28.6 = 29\ °\text{C}$$

Step 6: Determine the temperature at the aluminium-copper junction T_2

$$T_2 = \frac{3}{8} \times \frac{200}{7} = 10.7 = 11\ °\text{C}$$

Thermal Convection

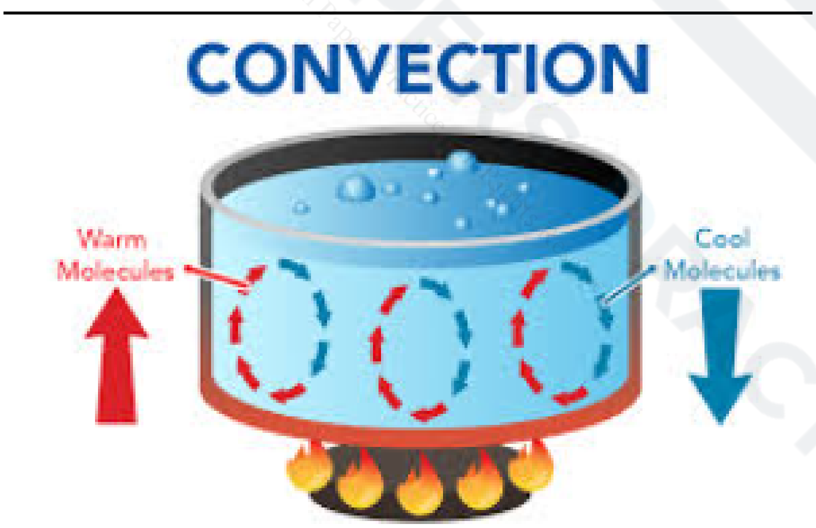
Thermal Convection

- Convection occurs when:

  A fluid is heated causing the movement of groups of atoms or molecules due to variations in density

- Convection is the main way that heat travels through **liquids** and **gases**
  - Convection **cannot occur in solids**
  - This is because the particles in a solid are unable to travel relative to one another
- When a fluid (a liquid or a gas) is heated from below:
  - The heated molecules gain kinetic energy and push each other apart, increasing the space between particles, thus making the fluid **expand**
  - This makes the hot part of the fluid **less dense** than the surrounding fluid
  - The **hot fluid rises** because of this, and the cooler (surrounding) fluid moves in to take its place
  - Eventually, the hot fluid cools, contracts and sinks back down again
  - The resulting motion is called a **convection current**

How is thermal energy transferred during convection?



The thermal energy from a fire forms a convection current in the air around it. The hot air rises and the cool air sinks.

Thermal Radiation

Black-Body Radiation

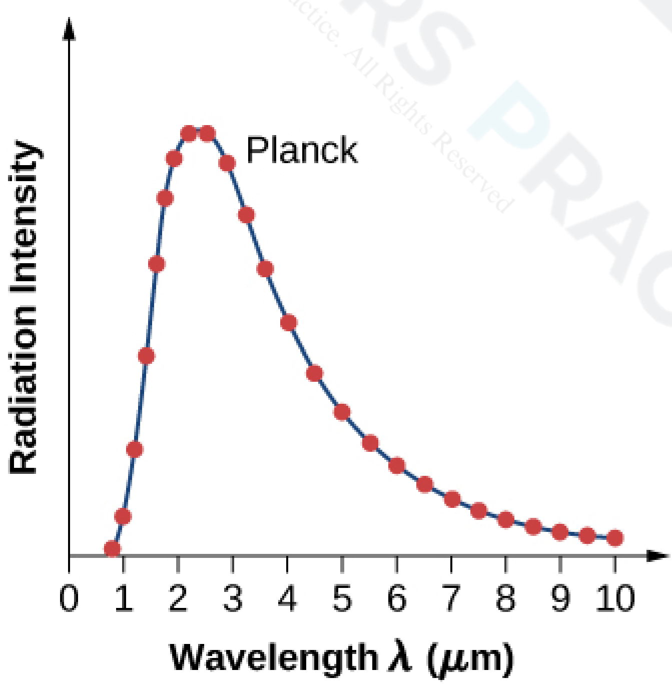
- Black-body radiation is the name given to the **thermal radiation** emitted by all bodies
  - Black-body radiation can be emitted in the form of infrared light, but also visible light or other wavelengths, depending on the temperature
- A perfect black body is defined as:

  An object that absorbs all of the radiation incident on it and does not reflect or transmit any

- Since a **good absorber** is also a **good emitter**, a perfect black body would be the best possible emitter too
- As a result, an object which completely absorbs all radiation will be black
  - This is because the colour black is what is seen when **all** colours from the visible light spectrum are absorbed

- The **intensity** and **wavelength** distribution of any emitted waves depends on the **temperature** of the body
- This can be represented on a black-body radiation curve of **intensity** against **wavelength**
  - As the temperature increases, the peak of the curve moves
  - This moves to a **lower** wavelength and a **higher** intensity

Black-body radiation curves



Black body spectrum for objects of different temperatures

- From the electromagnetic spectrum, waves with a **smaller** wavelength have **higher** energy (e.g. UV rays, X-rays)
  - The **hotter** the object, the **greater** the amount of infrared radiation it radiates in a given time
- A higher temperature increases the thermal energy emitted and therefore the **wavelength** of the radiation emitted at the greatest intensity, λ_{peak}, **decreases**
  - At room temperature, objects emit thermal radiation in the infrared region of the spectrum (λ_{peak} is in the infrared region)
  - At around 1000°C, an object will emit a significant amount of **red visible light** (λ_{peak} is in the red region of the visible spectrum)
  - At around 6000°C, an object will mainly emit **white** or **blue visible light** (λ_{peak} is in the centre or violet region of the visible spectrum)
  - At even higher temperatures, objects will emit **ultraviolet** or even **X-rays**

Thermal Radiation

- All bodies (objects), no matter what temperature, emit a spectrum of **thermal radiation** in the form of electromagnetic waves
  - These electromagnetic waves usually lie in the **infrared** region of the spectrum
- Thermal radiation is defined as:

Heat transfer by means of electromagnetic radiation normally in the infrared region

- The **hotter** the object, the **more** infrared radiation it radiates in a given time
  - This is because atoms and molecules above absolute zero are in constant motion
  - Electric charges within the atoms in a material vibrate causing **electromagnetic radiation** to be emitted
  - Therefore, the higher the **temperature**, the greater the **thermal motion** of the atoms and the greater the **rate** of emission of **radiation**
- Thermal radiation is the **only** method of thermal energy transfer that does not require **matter** in order to **move or propagate**
  - Therefore, thermal radiation is the only way heat can travel through a **vacuum**

- The amount of thermal radiation emitted by an object depends on a number of factors:
  - The **surface colour** of the object (black = more radiation)
  - The **texture** of the surface (shiny surfaces = more radiation)
  - The **surface area** of the object (greater surface area = more area for radiation to be emitted from)
- **Dark**, **dull** objects are **better** at **emitting** and **absorbing** radiation
- **Light**, **shiny** objects are **worse** at **emitting** and **absorbing** radiation

Worked example

A hot meteorite hits the surface of the Moon.

Identify and discuss the principal means by which the meteorite can dissipate thermal energy once it has landed.

Answer:

Step 1: Identify the types of thermal energy transfer

- An object can lose energy through conduction, convection or radiation
- In this case, the hot meteorite will only be able to lose energy via **conduction** and **radiation**

Step 2: Explain these choices

- The meteorite can lose heat energy through conduction because it is in contact with the surface of the Moon
- The Moon does not have an atmosphere, so convection is **not** possible
- Infrared photons emitted by the meteorite are able to travel through a vacuum, so heat loss via radiation **is** possible

Apparent Brightness & Luminosity

Apparent Brightness & Luminosity

- The apparent brightness b of a star is defined as:

  The intensity of radiation received on Earth from a star

- Apparent brightness is measured in **watts per metre squared (W m^{-2})**
- The apparent brightness of a star depends on two main factors:
  - How much light the star emits
  - How far away the star is (more distant stars are usually fainter than nearby stars)
- How much light the star emits is given by the luminosity L of the star, which is defined as:

  The total power output of radiation emitted by a star

- Luminosity is measured in units of **watts (W)**

- Knowing the luminosity and apparent brightness of a star is useful because it allows us to determine how far away it is from the Earth
- This is because
  - Luminosity tells us how bright the star is at its **surface**
  - Apparent brightness tells us how bright the star is as observed from the **Earth**
- Therefore, by the time the radiation from the distant star reaches the Earth, it will have spread out over a **very large area**
  - This means the intensity of the radiation detected on Earth will only be a **fraction** of the value of the star's luminosity

Inverse Square Law of Radiation

- A light source which is **further** away appears **fainter** because the light it emits is **spread out** over a greater area
- The moment the light leaves the surface of the star, it begins to spread out uniformly through a **spherical** shell
  - The surface area of a sphere is equal to $\mathbf{4\pi r^2}$
- The radius *r* of this sphere is equal to the distance *d* between the star and the Earth
  - By the time the radiation reaches the Earth, it has been spread over an area of $\mathbf{4\pi d^2}$
- This is called following an **inverse square law**
  - This phrase can be used to refer to any quantity whose intensity reduces by a factor equal to the square of the distance to the observer (e.g. the intensity of ionising radiation follows an inverse square law)
- The **inverse square law of radiation** can be written as:

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

- Where:
  - b = apparent brightness, or observed intensity on Earth (W m^{-2})
  - L = luminosity of the source (W)
  - d = distance between the star and the Earth (m)
- This equation assumes:
  - The power from the star radiates **uniformly** through space
  - No radiation is **absorbed** between the star and the Earth
- This equation tells us:
  - For a given star, the luminosity is **constant**
  - The intensity of the emitted light follows an inverse square law
  - For stars with the **same luminosity**, the star with the **greater** apparent brightness is **closer** to the Earth

Worked example

A star has a known luminosity of 9.7×10^{27} W. Observations of the star show that the apparent brightness of light received on Earth from the star is 114 nW m^{-2}.

Determine the distance of the star from Earth.

Answer:

Step 1: Write down the known quantities

- Luminosity, $L = 9.7 \times 10^{27}$ W
- Apparent brightness, $b = 114$ nW $m^{-2} = 114 \times 10^{-9}$ W m^{-2}

Step 2: Write down the inverse square law of radiation and rearrange for distance d

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

$$d = \sqrt{\frac{L}{4\pi b}}$$

Step 3: Substitute in the values and calculate the distance d

$$d = \sqrt{\frac{9.7 \times 10^{27}}{4\pi \times (114 \times 10^{-9})}}$$

distance, $d = 8.2 \times 10^{16}$ m

Stefan-Boltzmann Law

Stefan-Boltzmann Law

- The total power *P* radiated by a perfect black body depends on **two** factors:
  - Its absolute temperature
  - Its surface area
- The relationship between these is known as **Stefan's Law** or the **Stefan-Boltzmann Law**, which states:

  The total energy emitted by a black body per unit area per second is proportional to the fourth power of the absolute temperature of the body

- The Stefan-Boltzmann Law can be calculated using:

$$P = \sigma A T^4$$

- Where:
  - *P* = total power emitted across all wavelengths (W)
  - σ = the Stefan-Boltzmann constant
  - *A* = surface area of the body (m)
  - *T* = absolute temperature of the body (K)
- The Stefan-Boltzmann law is often used to calculate the luminosity of celestial objects, such as stars
  - Stars can be **approximated** as black bodies, as almost all radiation incident on a star is **absorbed**
  - The **power** emitted across all wavelengths, *P*, for a star is just its **luminosity**, *L*
- The surface area of a star (or other spherical object) is equal to $\boldsymbol{A = 4\pi r^2}$
  - Where *r* = radius of the star
- Substituting the above for area, *A*, the Stefan-Boltzmann equation then becomes:

$$L = 4\pi r^2 \sigma T^4$$

- Where:
  - *L* = luminosity of the star (W)
  - *r* = radius of the star (m)
  - σ = the Stefan-Boltzmann constant
  - *T* = surface temperature of the star (K)

Worked example

The surface temperature of Proxima Centauri, the nearest star to Earth, is 3000 K and its luminosity is 6.506×10^{23} W.

Calculate the radius of Proxima Centauri in solar radii.

Solar radius $R_\odot = 6.96 \times 10^8$ m

Answer:

Step 1: List the known quantities:

- Surface temperature, $T = 3000$ K
- Luminosity, $L = 6.506 \times 10^{23}$ W
- Stefan's constant, $\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4}
- Radius of the Sun, $R_\odot = 6.96 \times 10^8$ m

Step 2: Write down the Stefan-Boltzmann equation and rearrange for radius r

$$L = 4\pi R^2 \sigma T^4$$

$$R = \sqrt{\frac{L}{4\pi\sigma T^4}}$$

Step 3: Substitute the values into the equation

$$R = \sqrt{\frac{6.506 \times 10^{23}}{4\pi \times (5.67 \times 10^{-8}) \times 3000^4}}$$

Radius of Proxima Centauri: $R = 1.061 \times 10^8$ m

Step 4: Divide the radius of Proxima Centauri by the radius of the Sun

$$\frac{R}{R_\odot} = \frac{1.061 \times 10^8}{6.96 \times 10^8} = 0.152\ R_\odot$$

- Proxima Centauri has a radius which is about 0.152 times that of the Sun

Wien's Displacement Law

Wien's Displacement Law

- Wien's displacement law relates the observed wavelength of light from an object to its surface temperature, it states:

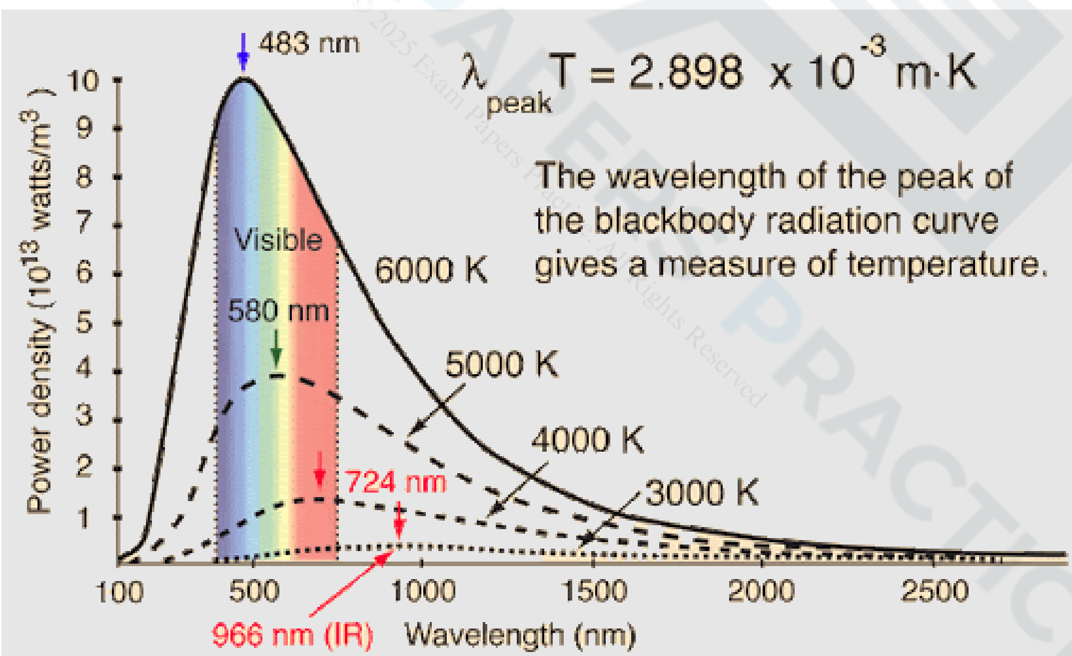
  The black body radiation curve for different temperatures peaks at a wavelength that is inversely proportional to the temperature

- This relation can be written as:

$$\lambda_{max} \propto \frac{1}{T}$$

- Where:
  - λ_{max} = the wavelength at which radiation is emitted at the greatest intensity (m)
  - T = the surface temperature of an object (K)

Wien's Displacement Law Graph



The intensity-wavelength graph shows how thermodynamic temperature links to the peak wavelength for four different bodies

- Wien's Law equation is given by:

$$\lambda_{max}T = 2.9 \times 10^{-3} \text{ m K}$$

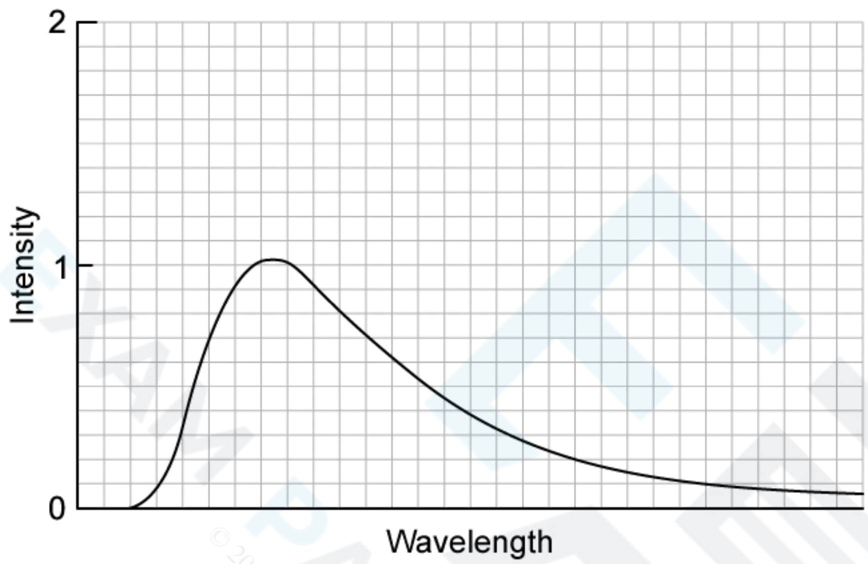
- This equation shows that the **higher the temperature** of a body, the **shorter the wavelength** at the peak intensity
  - Additionally, as the object gains temperature, the intensity of radiation at **every** wavelength increases – this can be seen on the graph above
- Consider an object being **heated** from room temperature:
  - Initially, the object emits radiation with the greatest intensity in the **infrared** range
  - As it gains heat, the peak of the curve shifts left to the **red region** of the **visible** spectrum (the object glows red)
  - As it is heated further, the peak shifts left further until it is in the **centre of the visible range**, (the object glows white, an equal mix of wavelengths in the visible range)
  - As it heats further still, the object will eventually glow blue and even emit UV radiation

Table to compare surface temperature and star colour

Star Colour	Temperature / K
blue	>33 000
blue-white	10 000 – 30 000
white	7500 – 10 000
yellow-white	6000 – 7500
yellow	5000 – 6000
orange	3500 – 5000
red	<3500

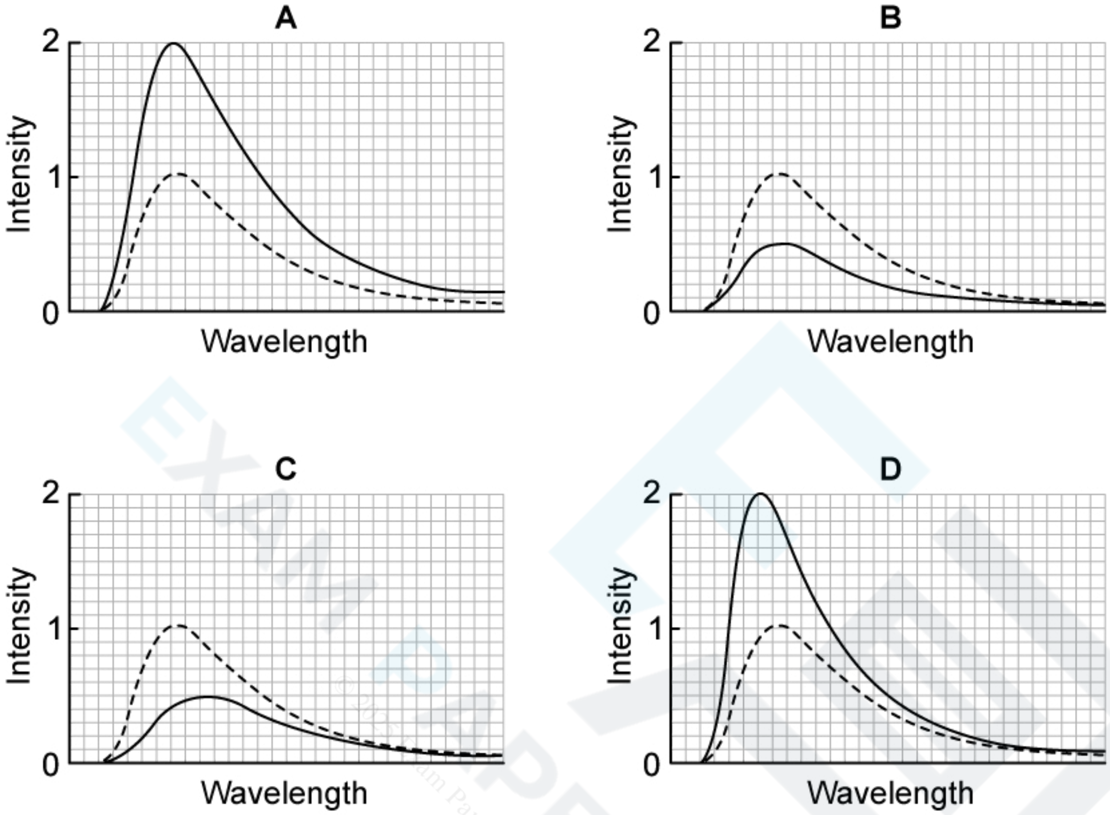
Worked example

The black-body radiation curve of an object at 900 K is shown in the diagram below.



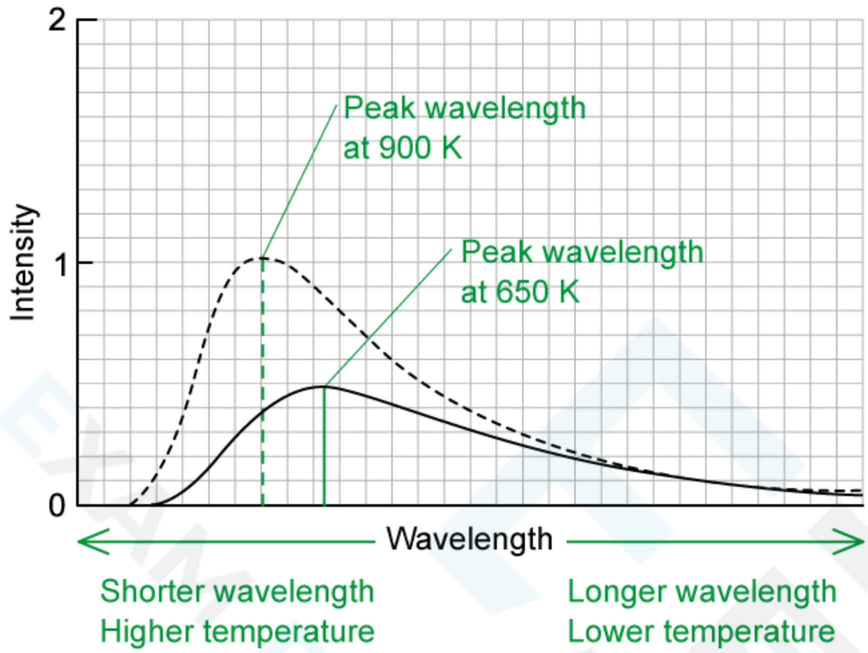
Which of the following shows the black-body radiation curve of an object at 650 K?

The dashed line represents the curve of the object at 900 K.



Answer: C

- From Wien's displacement law: $\lambda_{max} \propto \frac{1}{T}$
- Therefore, a curve with a **longer peak wavelength** will correspond to a **lower temperature**


2
1
0
Intensity
Peak wavelength
at 900 K
Peak wavelength
at 650 K
Wavelength
Shorter wavelength
Higher temperature
Longer wavelength
Lower temperature

Worked example

The spectrum of the star Rigel in the constellation of Orion peaks at a wavelength of 263 nm, while the spectrum of the star Betelgeuse peaks at a wavelength of 828 nm.

Determine which of these two stars, Betelgeuse or Rigel, is cooler.

Answer:

Step 1: List the known quantities

- Maximum emission wavelength of Rigel = 263 nm = 263 × 10^{-9} m
- Maximum emission wavelength of Betelgeuse = 828 × 10^{-9} m

Step 2: Write down Wien's displacement law and rearrange for temperature T

$$\lambda_{max} T = 2.9 \times 10^{-3} \text{ m K}$$

$$T = \frac{2.9 \times 10^{-3}}{\lambda_{max}}$$

Step 3: Calculate the surface temperature of each star

Rigel: $T = \dfrac{2.9 \times 10^{-3}}{263 \times 10^{-9}} = 11\,027 = 11\,000 \text{ K}$

Betelgeuse: $T = \dfrac{2.9 \times 10^{-3}}{828 \times 10^{-9}} = 3502 = 3500 \text{ K}$

Step 4: Write a concluding sentence

- Betelgeuse has a surface temperature of 3500 K, therefore, it is much cooler than Rigel

Wien's law and stars in the Orion constellation