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Reading assistance

(https://intercom.help/kognity)

TOPIC B
THE PARTICULATE NATURE OF MATTER

SUBTOPIC B.1
THERMAL ENERGY TRANSFERS

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The big picture

? Guiding question(s)

- How do macroscopic observations provide a model of the microscopic properties of a substance?
- How is energy transferred within and between systems?
- How can observations of one physical quantity be used to determine the other properties of a system?

Keep the guiding questions in mind as you learn the science in this subtopic. You will be ready to answer them at the end of this subtopic. The guiding questions require you to pull together your knowledge and skills from different sections, to see the bigger picture and to build your conceptual understanding.

In 1955, the United States and the Soviet Union announced, within three days of each other, their intentions to launch the world's first artificial satellite into space. So began the great Space Race, which would last almost two decades. During this time, both nations successfully launched artificial satellites into orbit around the Earth. They also developed rockets that carried fruit flies, dogs, plants, and even a chimpanzee, into space. Although there is no official winner of the Space Race, it is generally agreed that the race ended on 20th July 1969, when US astronaut Neil Armstrong became the first human to step foot on the Moon.

International Mindedness

The Space Race began as a competition between two nations. Now the International Space Station (ISS) is operated by a partnership of 16 nations that work together to provide the different parts of the ISS, coordinate safe launches, and provide training and fully functional

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communications systems. The astronauts on board the ISS come from several different countries and must live together in a very small space for an average of six months at a time.

What advantages do you think there are to this situation and these conditions?

What challenges could there be, and how would you suggest they could be overcome?

Astronauts on board the International Space Station (ISS) are regularly required to leave the space station for hours at a time in order to carry out maintenance and repairs (**Figure 1**).

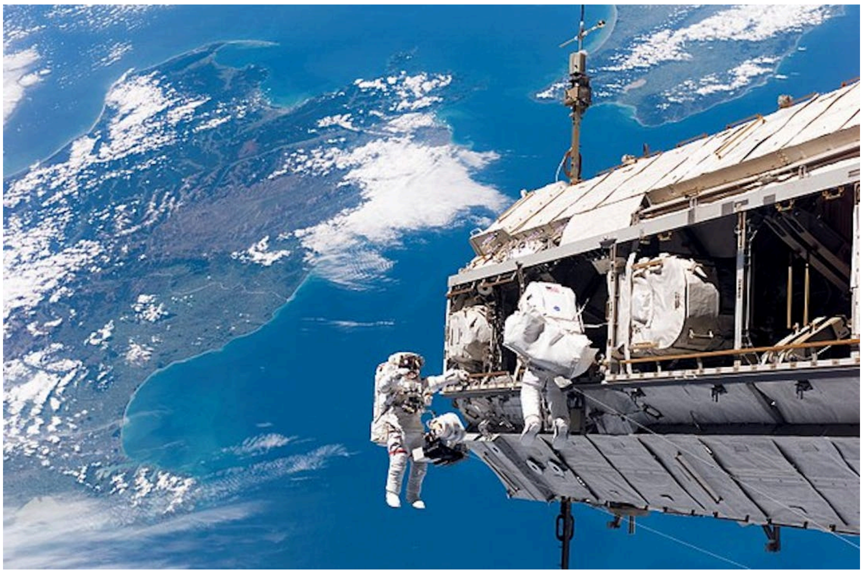

Figure 1. An astronaut carrying out a space walk outside the ISS.

Source: "STS-116 spacewalk 1 (https://commons.wikimedia.org/wiki/File:STS-116_spacewalk_1.jpg)" by NASA is in the public domain

An astronaut's space suit needs to protect them from dangers in space, allow them to move comfortably, and maintain all parts of their body at a comfortable temperature.

The temperature outside the ISS ranges from –160 °C on the side facing away from the Sun to 120 °C on the side facing the Sun. This leads to a challenging design problem – how do we design a space suit that keeps astronauts cool when it is hot but also keeps them warm when it is freezing?

In this subtopic, you will develop your understanding of some of the key physics theories that are essential to developing an effective solution to this problem.

Concept

What role does the molecular model play in understanding other areas of physics?

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A particle can be described as a unit of matter. Throughout this subtopic, the word particle will be used to describe a single unit of the substance being described. In monatomic substances, a particle is a single atom. When atoms are bonded to form molecules, each molecule will be considered a particle.

The physical laws that govern the interaction between particles allow us to explain a wide range of observable phenomena. Although these particles are too small to observe in a high school laboratory we can make deductions and inferences about the constituents of matter based on our observations of factors such as pressure, volume, temperature.

Prior learning

Before you study this subtopic, make sure that you understand the following:

- Names of changes of state (pre-IBDP science curriculum).
- Kinetic and potential energy (subtopic A.3 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43083/)).

Practical skills

Once you have completed this subtopic, you can apply your knowledge of energy transfers by going to Practical 3: Measuring the specific latent heat of vaporisation of water (/study/app/math-aa-hl/sid-423-cid-762593/book/measuring-the-specific-latent-heat-of-vaporisation-of-water-id-46752/).

B. The particulate nature of matter / B.1 Thermal energy transfers

Molecular theory in solids, liquids and gases

B.1.1: Molecular theory in solids, liquids and gases B.1.2: Density B.1.6: The internal energy of a system

Learning outcomes

By the end of this section you should be able to explain the molecular structure of solids, liquids and gases.

Look at **Figure 1**. Sort the objects into groups. There is no right or wrong answer, but you should be able to justify your choice. Discuss your ideas with your classmates.

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Figure 1. Sort the objects into groups.

Some of you may have sorted the items according to whether the objects were solids, liquids or gases. The phase of matter of a given substance is dependent on the arrangement and behaviour of its particles.

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Solids

Solids have the following properties:

- They have a fixed volume and do not flow.
- The particles are arranged in regular rows.
- The particles have relatively little energy and vibrate around fixed positions.
- The particles have relatively strong forces of attraction between them, called intermolecular forces.
- When a solid is heated, the particles gain energy and move further apart, weakening the intermolecular forces.
- This results in the thermal expansion of the solid. For the same increase in temperature, a substance in its solid phase expands less than the same substance in its liquid and gaseous phases.

Interactive 1 shows the molecular arrangement in a solid.

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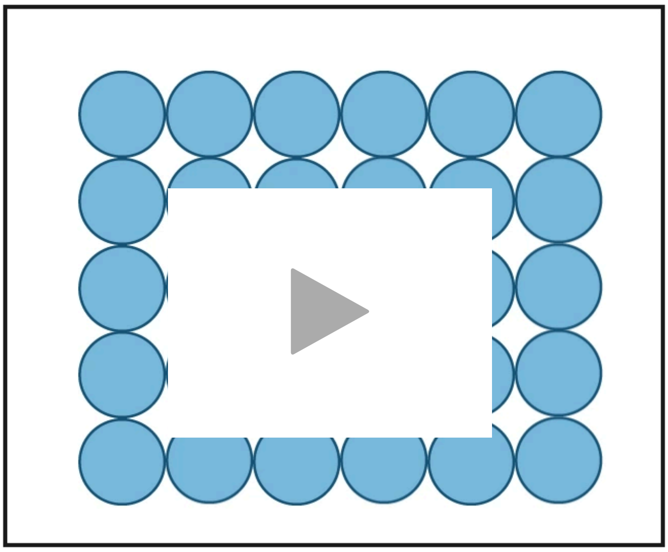

Interactive 1. The Molecular Arrangement in a Solid.

More information for interactive 1

The animated video shows the molecular arrangement in a solid. The particles are represented as spheres arranged in a regular, tightly packed pattern. They remain in fixed positions but vibrate slightly, demonstrating how particles in a solid have limited movement. The animation highlights the strong intermolecular forces that hold the particles close together and prevent them from flowing.

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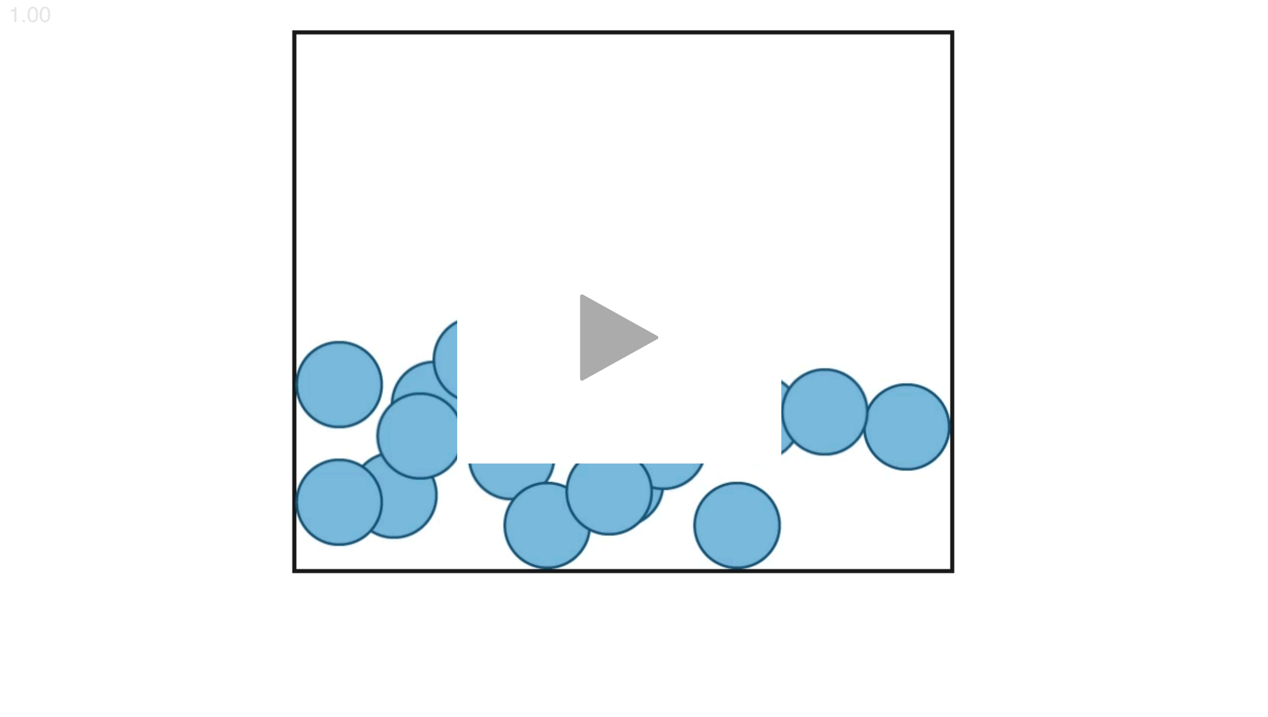
Liquids

Liquids have the following properties:

- They can flow and take the shape of their container.
- The particles are arranged randomly.
- The particles have more energy than those in a solid of the same substance and can move around each other.
- The strength of the intermolecular forces is weaker than in a solid of the same substance, but stronger than in a gas of the same substance.
- When a liquid is heated, the particles gain energy and move further apart, weakening the intermolecular forces.
- This results in the thermal expansion of the liquid. For the same increase in temperature, a substance in its liquid phase expands more than the same substance in its solid phase but less than the substance in its gaseous phase.

Interactive 2 shows the molecular arrangement in a liquid.



Interactive 2. The Molecular Arrangement in a Liquid.

More information for interactive 2

The animation video shows the molecular arrangement in a gas. The animation shows the movement of gas molecules inside a container. The molecules are represented as blue circles that move freely in different directions. They are spaced relatively far apart and collide with each other and the walls of the container. The motion is random and continuous, demonstrating the high energy and rapid movement of gas particles. The video effectively illustrates the characteristic behavior of gases, where the particles do not have a fixed arrangement and can occupy the entire volume of the container.

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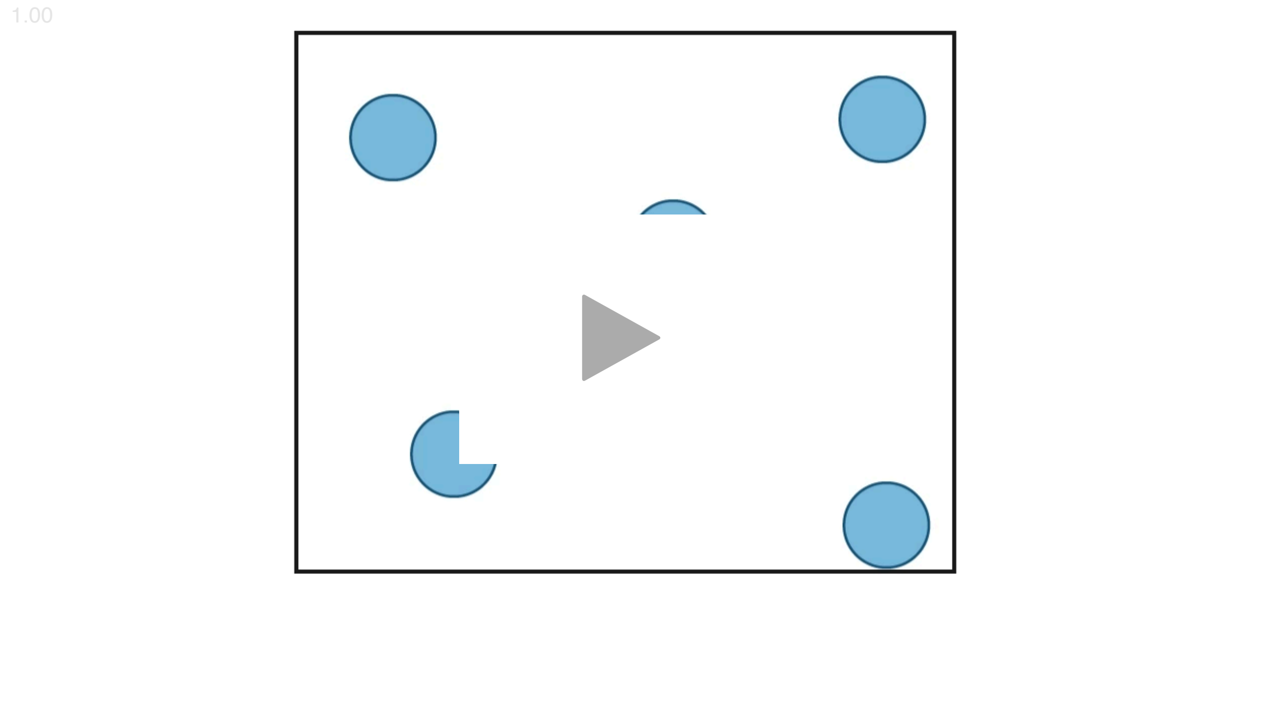
Gases

Gases have the following properties:

- They can flow and fill their container completely.
- Their volume can change by altering the pressure and/or temperature.
- The particles are comparatively far apart and in a random arrangement.
- Compared to the solid and liquid states of the same substance, the particles have high amounts of energy and move quickly in all directions.
- For the same increase in temperature, a substance in its gaseous phase has the largest thermal expansion.

Interactive 3 shows the molecular arrangement in a gas.



Interactive 3. The molecular arrangement in a gas.

Study skills

Liquids and gases are sometimes referred to as **fluids** because they can **flow**.

Use **Interactive 4** to check your understanding of the properties of solids, liquids and gases. Drag and drop the words ‘solid’, ‘liquid’ and ‘gas’ into the correct places.

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Interactive 4: Properties of States of Matter: Key Terms

Theory of Knowledge

In this subtopic, visual representations are used to help you understand how particles behave. These visual representations are often flawed. How do scientists use visual representations to communicate knowledge? Does it matter that they are almost always flawed?

Internal energy

Imagine looking up into the sky to see it filled with hot air balloons (**Figure 2**). The balloons are filled with gas, but what are the gas particles doing?

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Figure 2. What are the gas particles doing inside a hot air balloon?

Credit: Westend61, Getty Images

The gas particles inside the balloon are moving around randomly, so they have kinetic energy (this is the microscopic energy of the particles moving randomly, not the macroscopic energy of the balloon moving). They are also experiencing intermolecular forces and these forces give rise to intermolecular potential energy. The sum of these two types of energy is known as the internal energy.

It is common to consider the change in internal energy of a system. The internal energy can change due to either a change in kinetic energy resulting in a change in temperature (see section B.1.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/temperature-scales-id-44050/)) or a change in potential energy, which may result in a change of phase (see section B.1.3 (/study/app/math-aa-hl/sid-423-cid-762593/book/changing-temperature-and-changing-phase-id-44051/)).

When a substance is in its solid phase, its particles have the lowest kinetic energy. The particles are closer together than the particles in liquids and gases, so they have the lowest potential energy. When the same substance is in its gaseous phase, its particles have the highest kinetic and potential energies, and therefore the highest internal energy.

More generally, intermolecular potential energy is negative because molecules tend to be attracted to each other. This means that, as the molecules get closer together, their potential energy decreases, and as they get further apart, their potential energy increases. This means that work must be done to bring molecules apart, and this work corresponds to the increase in the molecules’ potential energy. The highest possible value of intermolecular potential energy is zero, since that is the value of potential energy the molecules would have if there was no interaction between them. For all these reasons, intermolecular potential energy is negative.

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Interactive 5 shows that as the kinetic energy of particles increases, they vibrate more and they move further apart, increasing their potential energy.

Interactive 5. The Potential and Kinetic Energies of Particles.

More information for interactive 5

The interactivity consists of three panels, each containing a two-second video of two red balls connected by a wavy line, representing a simple oscillatory motion. The system behaves like a molecular vibration or a coupled oscillator, where the balls perform a see-saw action.

In the top panel, the balls are shown in an intermediate position, neither too far apart nor too close together. The wavy connection suggests a flexible bond, indicative of a balanced state between kinetic and potential energy. The balls appear to be oscillating around a central position, demonstrating the continuous energy exchange between kinetic and potential forms.

The bottom left panel represents a state of greater kinetic energy. The balls are closer together, and the wavy connection appears to be less stretched. This system is moving faster, with the energy being concentrated in motion rather than in stored potential energy. The rapid motion indicates that the system is near equilibrium, where kinetic energy is maximized.

The bottom right panel represents a state of greater potential energy. The balls are farther apart, and the wavy connection is stretched significantly. This system has stored energy due to the increased separation.

The interactivity demonstrates the interplay between kinetic and potential energy in an oscillating system. Users can observe how energy shifts dynamically, with kinetic energy peaking when the balls are closest together and potential energy peaking when they are farthest apart.

Making connections

The kinetic energy of translational motion, which results in the change in position of a macroscopic object, is given by $E_\mathrm{k} = \frac{1}{2}mv^2$ (see section A.3.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/work-and-energy-id-43084/)).

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This kinetic energy is different to the random kinetic energy of the molecules of a substance, which does not result in the change in position of a macroscopic object.

Which do you think has the greatest internal energy? A box at rest or an identical box sliding at a constant speed on a frictionless surface?

The two boxes have the same internal energy (provided the atmospheric conditions are the same). The moving box has more macroscopic kinetic energy, but this is not the same as the molecular random kinetic energy. The internal energy of the gas particles is independent from the position and translational motion of the container.

Density

The density of a substance is defined as the mass per unit volume. The greater the mass of $1\,m^3$ of a substance, the greater its density. The unit of density is kilograms per cubic metre ($kg\,m^{-3}$). The closer together the molecules are in a substance, the greater its density. **Figure 3** shows the densities of the same substance in two states of matter – a dense state and a less dense state.

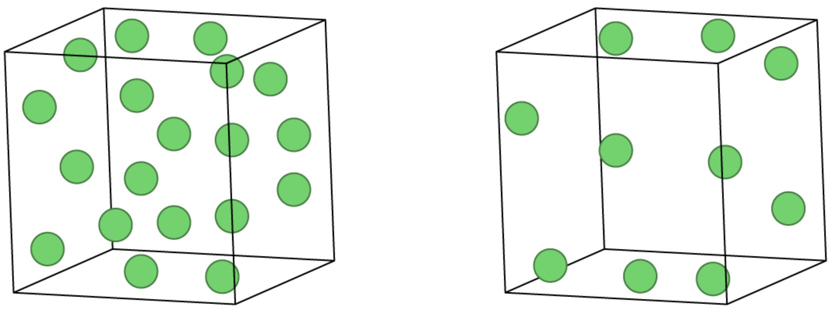

Figure 3. The molecular arrangement of the same substance in two different states of matter having different densities.

More information for figure 3

This diagram illustrates the molecular arrangement of the same substance in two different states of matter, each with distinct densities. On the left side, molecules are depicted as closely packed, indicating a denser state. The molecules appear in a more structured and compact formation. On the right side, the molecules are shown more spaced apart, representing a less dense state with a looser arrangement. Each molecule is shown in green, and the diagram clearly delineates the difference in spacing between the two states, emphasizing how molecular proximity impacts density.

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Density can be calculated using the equation:

Table 1. Calculating the density of a substance.

Equation	Symbols	Units
$\rho = \frac{m}{V}$	ρ = density	kilograms per cubic metre (kg m^{-3})
	m = mass	kilogram (kg)
	V = volume	cubic metres (m^3)

Study skills

Converting between mm^3 and m^3

Because you are working with mm^3, the volume must be divided by 1000 **three** times, in other words, by 1000^3.

Converting between cm^3 and m^3

In the same way, to convert from cm^3 to m^3, you must divide the volume by 100^3.

Worked example 1

During an experiment, the mass of a copper cube, with sides of length 20.0 mm, is measured to be 72 g.

Calculate the density of the copper cube.

Solution steps	Calculations
Step 1: write out the values given in the question and convert the values to the units required for the equation	$m = 72\text{ g} = 72 \times 10^{-3}\text{ kg}$ $l = 20.0\text{ mm} = 20.0 \times 10^{-3}\text{ m}$
Step 2: calculate the volume of the cube	$V = l^3$ $= (20.0 \times 10^{-3})^3$ $= 8 \times 10^{-6}\text{ m}^3$
Step 3: write out the equation	$\rho = \frac{m}{V}$

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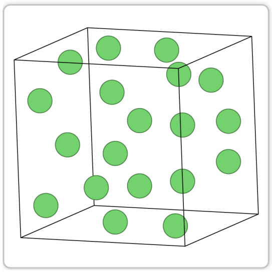
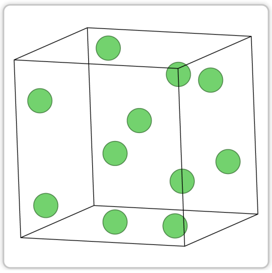
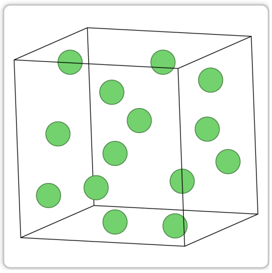
Solution steps	Calculations
Step 4: substitute the values given	$=\dfrac{72\times10^{-3}}{8\times10^{-6}}$
Step 5: state the answer with appropriate units and the number of significant figures used in rounding	$=9000\ \text{kg m}^{-3}\ (2\ \text{s.f.})$

The boxes in **Interactive 6** contain the same substance (containing identical particles). Drag the boxes into the correct order with the least dense on the left and the most dense on the right.

Least dense **Most dense**







Check

Interactive 6. Order the substances from least dense to most dense.

Aspect: Theories

What role does the molecular model play in understanding other areas of physics?

Humans have been theorising about matter for over 2000 years. Over the last two centuries, our understanding of what makes up everything in the Universe has developed significantly. Watch the video and consider the following:

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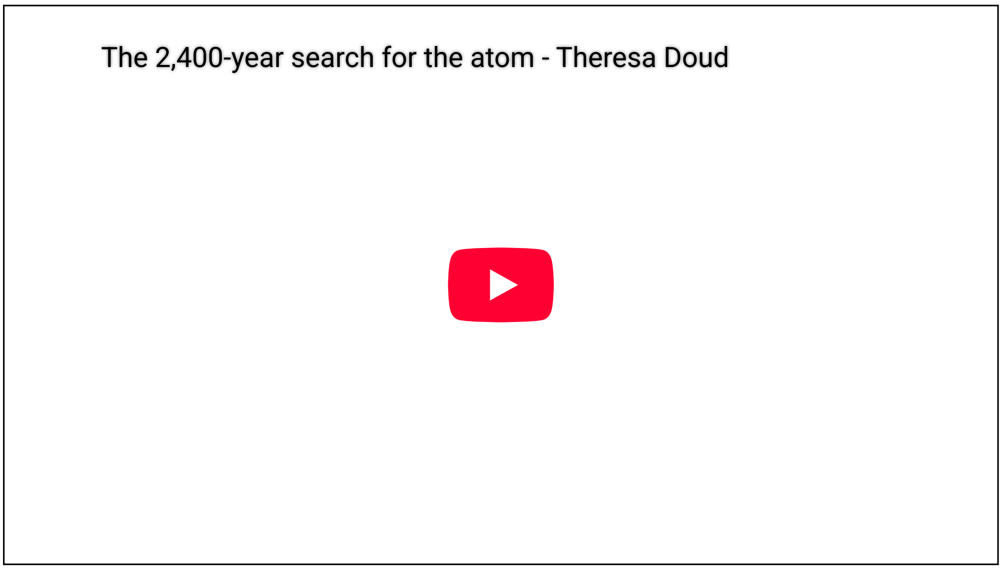
- Compare the theories — what are the similarities and differences between them?
- How do theories about molecules, atoms and subatomic particles help you to understand other areas of physics, such as nuclear physics?
- Suggest what you think might happen next — will the molecular model develop further?



Video 1. What is stuff made of?

Try the following activity to check your understanding of the molecular structure of the different phases of matter.

Activity

- **IB learner profile attribute:** Communicator
- **Approaches to learning:** Thinking skills — Designing procedures and models
- **Time required to complete activity:** 30 minutes
- **Activity type:** Pair activity

Your task is to make a digital flipbook to show the microscopic changes when a substance changes phase. It should include information about:

- How the particles are arranged in each phase.
- The amount of energy (or speed) the particles have in each phase.
- The motion of the particles in each phase.
- A consideration of the distances between particles in each phase.

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If you have access to a camera and a computer, you can make a stop-motion video by taking lots of photographs, then editing them together to make a short film. You could also use modelling clay, whiteboards and erasable markers, or recycled items such as bottle caps to make your animation. Alternatively, this task can be completed using apps available on mobile phones and tablets.

5 section questions

Question 1

SL HL Difficulty:

In which phase of matter do molecules have the most kinetic energy?

1 gas ✓

2 liquid

3 solid

4 The kinetic energy of the molecules is the same in all phases of matter

Explanation

Molecules have the most kinetic energy in the gas phase because they are moving the fastest.

Question 2

SL HL Difficulty:

Density is a measure of the 1 mass ✓ per unit 2 volume ✓ of a substance.

Accepted answers and explanation

#1 mass

#2 volume

General explanation

The density of a substance gives you the mass in kg of 1 m^3.

Question 3

SL HL Difficulty:

The mass of an aluminium cube of volume 1.8 m^3 is 4880 kg. Calculate the density of the aluminium cube.

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1 2700 kg m^{-3} ✓

2 2710 g m^{-3}

3 2 700 000 kg m^{-3}

4 2 710 000 m^{-3}

Explanation

$m = 4880 \text{ kg}$

$V = 1.8 \text{ m}^{-3}$

$$\begin{aligned}\rho &= \frac{m}{V}\\ &= \frac{4880}{1.8}\\ &= 2711\\ &= 2700 \text{ kg m}^{-3} \text{ (2 s.f.)}\end{aligned}$$

Question 4

SL HL Difficulty:

A block of wood with mass 1.44 kg has a density of 1500 kg m^{-3}. What is its volume?

1 960 cm^3 ✓

2 2160 m^3

3 2200 m^3

4 1 × 10^9 mm^3

Explanation

$m = 1.44 \text{ kg}$

$\rho = 1500 \text{ kg m}^{-3}$

$\rho = \dfrac{m}{V}$

$$\begin{aligned}V &= \frac{m}{\rho}\\ &= \frac{1.44}{1500}\\ &= 9.6\times10^{-4} \text{ m}^3\end{aligned}$$

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Convert to cm^3:

$$9.6 \times 10^{-4} \times 100^3 = 960 \text{ cm}^3 \text{ (2 s.f.)}$$

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Question 5

SL HL Difficulty:

An aluminium sphere of radius 20 mm has a mass of 96 g. Calculate the density of aluminium. Give your answer to an appropriate number of significant figures.

The density of aluminium is 1 2900 ✓ kg m^{-3}

Accepted answers and explanation

#1 2900

2,900

2.9x10^3

2.9*10^3

General explanation

$$m = 96\times10^{-3}\text{ kg}$$

$$r = 20\times10^{-3}\text{ m}$$

$$\begin{aligned}V\text{ of sphere} &= \frac{4}{3}\pi r^3\\ &= \frac{4}{3}\pi\left(20\times10^{-3}\right)^3\\ &= 3.35\times10^{-5}\text{ m}^3\end{aligned}$$

$$\begin{aligned}\rho &= \frac{96\times10^{-3}}{3.35\times10^{-5}}\\ &= 2865.672\\ &= 2900\text{ kg m}^{-3}\text{ (to 2 s.f.)}\end{aligned}$$

B. The particulate nature of matter / B.1 Thermal energy transfers

Temperature scales

B.1.3: Kelvin and Celsius scales B.1.4: Temperature change B.1.5: Kelvin temperature and the average kinetic energy of particles

Learning outcomes

By the end of this section you should be able to:

- Recognise that different temperature scales are used around the world, but they fundamentally describe the same thing.

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- Explain that there is a difference between the numerical values of Kelvin and Celsius temperature scales, but no difference in the magnitude of the change of temperature on these scales.
- Explain that Kelvin scale of temperature is a measure of the average kinetic energy of particles as given by:

$$\bar{E}_\mathrm{k} = \frac{3}{2} k_\mathrm{B} T$$

Watch **Video 1** and write down the following:

- One fact shared in the video.
- One useful application of the information shared in the video.
- One question you have after watching the video.

Video 1. There is no such thing as cold.

You are probably familiar with the Celsius scale of temperature measurement, whose unit is the degree Celsius. Using this scale, the freezing temperature of pure water is 0 °C and the boiling temperature is 100 °C. While this system is appropriate for everyday use, scientists often use another temperature scale, known as the Kelvin scale.

Temperature is a useful measurement as it tells us the direction of net thermal energy transfer, so it’s important to be clear about which units are being used.

Absolute temperature and the Kelvin temperature scale

If the temperature of a gas is decreased what will happen to its pressure?

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Explore what happens to a gas when its temperature decreases using **Interactive 1**.

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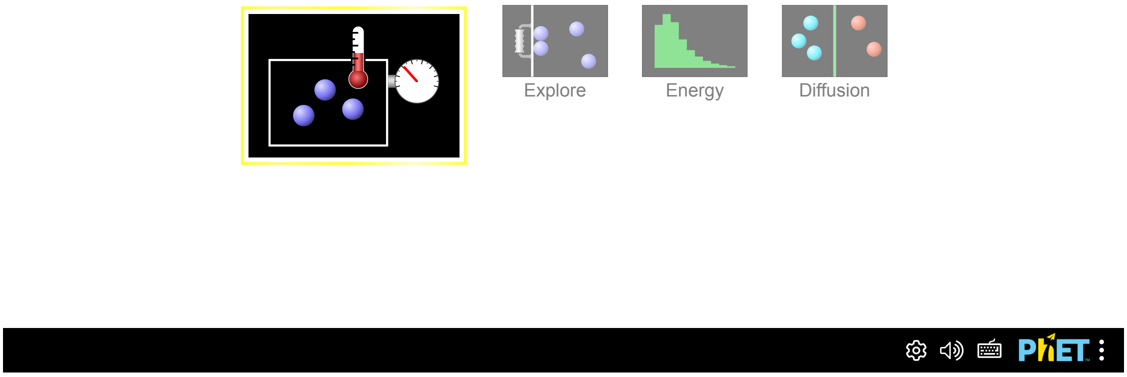
- Select ‘Ideal’.
- Use the ‘Particles’ box to add gas particles to the container. Once you have decided how many particles to add, do not add any more.
- Click the down arrow above the thermometer to change the units to °C.
- Click the down arrow below the pressure gauge to change the units to kPa.
- Record the temperature and average pressure in a suitable table.
- Use the Heat and Cool slider to decrease the temperature of the gas. Record the average value shown for the new pressure.
- Repeat for seven different values of temperature.
- Plot a graph of pressure in kPa on the *y*-axis against temperature in °C on the *x*-axis.
- Draw an appropriate line of best fit.
- At what temperature is the pressure of the gas zero? Click the Show or hide solution button to reveal the answer.

You can make the simulation larger by clicking on the three dots in the bottom right-hand corner and selecting the Full screen option.

The temperature at which the pressure of the gas is zero is –273 °C.



Interactive 1. Properties of an ideal gas.

More information for interactive 1

The Gas Properties interactive simulation explores the behavior of an ideal gas through four modules: Ideal, Explore, Energy, and Diffusion. The Ideal module focuses on investigating temperature, pressure, volume, and particle interactions in a gas system, helping users understand fundamental gas laws and kinetic molecular theory.

Users can manipulate variables such as temperature, pressure, volume, and particle number to observe real-time changes in gas behavior. The simulation features a gas container where particles move randomly after being introduced via a hand pump, along with a thermometer, pressure gauge, and heating/cooling unit for modifying thermal energy. By introducing light or heavy gas

Student view

particles, users can explore how different conditions affect gas properties. The control panel allows users to hold certain variables constant, such as volume or pressure, enabling targeted investigations into gas laws like Boyle's and Charles' laws. Additional tools, including a stopwatch, collision counter, and width adjustment, enhance data collection and analysis.

Through this interactive simulation, users gain a deeper understanding of the statistical nature of gas behavior. They can observe how pressure fluctuates due to particle collisions with the container walls and how temperature changes influence particle motion and pressure. By conducting experiments, recording multiple temperature and pressure values, and calculating uncertainties, users develop experimental and data analysis skills. The simulation reinforces the direct relationship between temperature and pressure at constant volume, demonstrating the kinetic molecular theory in action and emphasizing the impact of temperature on molecular motion.

When the temperature of a gas is decreased, the pressure and volume of the gas, and the kinetic energy of its molecules, will decrease towards zero. At this point, the temperature of the gas will be −273 °C.

This can be seen from a graph of the pressure (or volume) of a gas against its temperature in degrees Celsius (**Figure 1**).

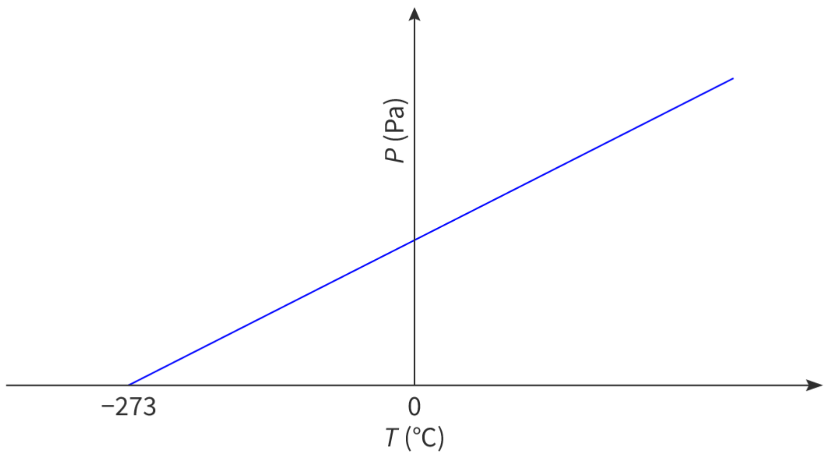


Figure 1. Graph of pressure against temperature for an ideal gas.

More information for figure 1

The graph represents a plot of pressure (P) in pascals (Pa) against temperature (T) in degrees Celsius (°C) for an ideal gas. The X-axis is labeled as temperature (T) with values starting from -273 (left) up to an unlabeled positive value, with a prominent mark at 0 °C. The Y-axis represents pressure (P) in pascals, beginning from zero at the origin and extending upwards. The line starts from the X-axis at -273 °C, indicating the point at absolute zero where pressure is theoretically zero, and ascends linearly as temperature increases, following the ideal gas law trend. The graph illustrates that pressure and temperature of an ideal gas are directly proportional, evident from the linear increase observed in the plot.

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In 1848, a Scottish physicist, William Thomson (also known as Lord Kelvin), proposed a new temperature scale using the temperature at which the pressure and volume of a substance is equal to zero, as absolute zero, or zero kelvin (0 K). **Figure 2** shows the Celsius and Kelvin temperature scales.

Study skills

A temperature given using the Kelvin scale is known as the absolute temperature of a substance.

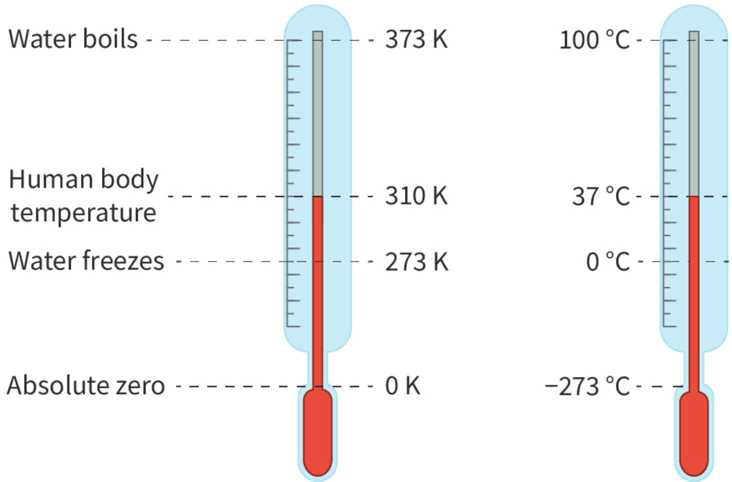

Figure 2. The Kelvin and Celsius temperature scales.

More information for figure 2

The image displays two thermometers side by side to compare the Kelvin and Celsius temperature scales. On the left, the Kelvin scale thermometer lists the following points: Water boils at 373 K, Human body temperature at 310 K, Water freezes at 273 K, and Absolute zero at 0 K. On the right, the Celsius scale thermometer shows these points: Water boils at 100°C, Human body temperature at 37°C, Water freezes at 0°C, and Absolute zero at -273°C. Both thermometers have a similar graphical representation, with a colored liquid indicating the different temperature markers on each scale.

[Generated by AI]

Theory of Knowledge

Absolute zero is the temperature at which the molecules of a substance have minimum energy. However, this temperature has never been reached. In the formulation of absolute zero and the Kelvin temperature scale, what role do you think inductive and deductive

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reasoning have played?

Converting between kelvin and degrees Celsius

As −273 °C is the same as 0 K, you can convert from °C to K by adding 273.

To convert from K to °C, subtract 273.

temperature (K) = temperature (°C) + 273

temperature (°C) = temperature (K) − 273

Study skills

Temperatures on the Kelvin scale are in kelvin (K), **not** degrees kelvin (°K).

A temperature change of 1°C is the same as a temperature change of 1 K.

$$\Delta T(^{\circ}\mathrm{C}) = \Delta T(\mathrm{K})$$

Check your understanding of how to convert between kelvin and degrees Celsius by answering the question.

Exercise 1

Click a question to answer

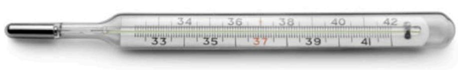
Match each temperature in °C with a temperature in K in **Interactive 2**.

Student view

Interactive 2. Match the Temperatures in Degrees Celsius and Kelvin.

Measuring temperature

Temperature is measured using a thermometer. There are many different types of thermometers, from the traditional liquid-in-glass thermometer to digital thermometers (**Figure 3**). Digital thermometers use a thermistor, whose resistance varies depending on the temperature.



Credit: Floortje, Getty Images

Credit: deepblue4you, Getty Images

Credit: Edwin Tan, Getty Images

Credit: Science Photo Library - IAN HOOTON, Getty Images

Figure 3. Different types of thermometers.

In order to set the scale on a liquid-in-glass thermometer, the thermometer must be calibrated. This means that the measurements of the thermometer must be correlated with known temperatures in order to make sure it is accurate. These temperatures can be, for example, the ice point (0 °C) and the steam point (100 °C) of water. You can try this at home with the following activity.

Activity

- **IB learner profile attribute:** Inquirer
- **Approaches to learning:** Self-management skills — Breaking down major tasks into a sequence of steps
- **Time required to complete activity:** 30 minutes

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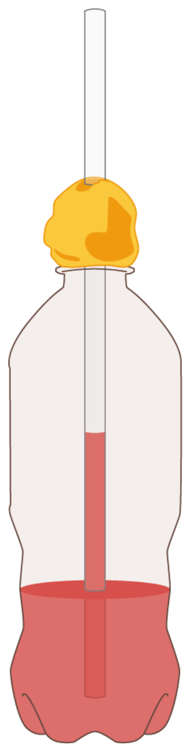
- **Activity type:** Pair/group activity

Apparatus

- 1 small plastic bottle
- 1 lump of modelling clay
- 1 thin glass capillary (or a clear plastic straw)
- Ethanol, or a mix of at least 50% ethanol and water
- Food colouring
- A permanent marker
- A container of ice cubes
- A container filled with boiling water
- 1 syringe

Method

1. Half-fill the bottle with ethanol.
2. Add a few drops of food colouring.
3. Place the straw into the bottle so that it is in the water but not touching the bottom of the bottle.
4. Seal the bottle with the modelling clay so that the straw is held firmly in place and the opening of the bottle is airtight.



More information

Student view

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The image depicts a bottle rocket experiment. A plastic soda bottle serves as the main body, partially filled with red liquid. At the top, a yellow balloon is attached securely around the neck of the bottle. A straw is inserted through the balloon's neck and extends upwards. This setup is typically used for demonstrating principles of physics like propulsion and pressure.

[Generated by AI]

1. The coloured ethanol should rise up the straw.
2. Place the bottle into the container of ice cubes and observe the movement of the ethanol in the straw.
3. When the ethanol reaches its lowest level, use the marker pen to mark a line on the straw at the level of the ethanol. This is the ethanol's ice point.
4. If the ethanol is below the top of the bottle, so that it is not possible to mark the straw, use the syringe to slowly add more ethanol, leaving time for the ethanol to respond to the cold of the ice.
5. Now place the bottle into the container of boiling water and observe the rise in height of the ethanol in the straw.
6. When the ethanol reaches its highest level, use the marker pen to mark a line on the straw at the level of the ethanol. This is the ethanol's steam point.
7. Use a ruler to divide the length of the straw between the ice point and steam point marks into 100. Now you have your own thermometer.

Note: It may take some trial and error to get the initial volume of ethanol in the bottle correct so that when the bottle is in ice, the ethanol does not drop in height below the top of the bottle, and when the bottle is in boiling water, the ethanol does not expand so much that it comes out of the top of the straw. Be patient — this is what science is all about.

Nature of Science

Aspect: Global impact of science

The invention of the liquid-in-glass thermometer is credited to the German physicist Daniel Gabriel Fahrenheit in the 18th century. The liquid in the thermometer was traditionally mercury because, for a small increase in temperature, it has a large expansion, meaning it can measure smaller changes in temperature than other liquids.

Mercury was widely used in thermometers for over two centuries. However, it is highly toxic to humans and can be very harmful if inhaled, ingested or in contact with the skin. As thermometers are made from glass and break easily, this makes mercury thermometers a safety hazard.

The liquid now used in most thermometers is the hydrocarbon kerosene, which is about five times less sensitive than mercury but much less harmful. Is a reduced risk to the health of animals and the environment worth a reduction in scientific accuracy?

Student view

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Temperature changes

In the Kelvin scale, the difference between the freezing point and boiling point of water is divided into 100, meaning that a temperature change of 100 °C is the same as a temperature change of 100 K. This means that a temperature change in degrees Celsius is the same as a temperature change in kelvin.

Worked example 1

Water is heated from 18 °C to 100 °C.

Calculate the change in temperature in kelvin.

$$T_1 = 18\ ^\circ\mathrm{C}$$

$$T_2 = 100\ ^\circ\mathrm{C}$$

$$\Delta T\ =\ T_2 - T_1$$

It is not necessary to convert the temperatures to kelvin first, as the temperature change in °C is the same as the temperature change in K.

$$\begin{aligned}\Delta T &= 100 - 18\\ &= 82\ \mathrm{K}\end{aligned}$$

International Mindedness

The General Conference of Weights and Measures defined for the international community that the kelvin is one of the seven fundamental SI units. Having consistent units helps scientists communicate accurately and ensure they are measuring the same variables in the same way, no matter where they are in the world.

But these units aim to replace others which were developed by a wide range of cultures from antiquity all the way up to the present day. To what extent does the benefit to scientific accuracy and communication outweigh the loss of cultural and historical knowledge?

Kelvin temperature and the average kinetic energy of molecules

The kinetic energy of the particles of a substance is zero when its absolute temperature is zero kelvin (0 K). Kinetic energy is proportional to temperature, as shown in the graph in **Figure 4**.

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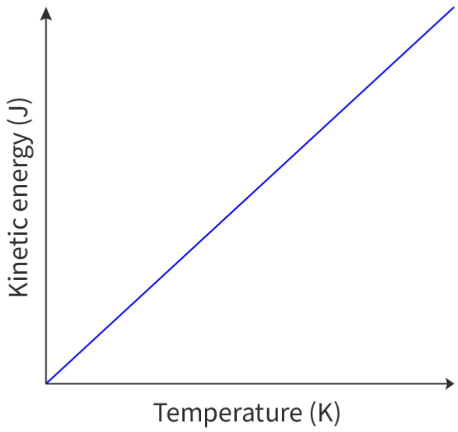

Figure 4. Graph of temperature versus kinetic energy for a substance.

More information for figure 4

The graph displays a straight line representing the relationship between kinetic energy and temperature for a substance. The x-axis is labeled as "Temperature (K)" indicating that it measures temperature in Kelvin. The y-axis is labeled as "Kinetic Energy (J)", which measures kinetic energy in Joules. The line starts at the origin, indicating zero kinetic energy at zero Kelvin, and extends linearly, showing that kinetic energy is directly proportional to temperature. This linear relationship follows the equation E_k = mT, where m represents the gradient, equal to 3/2 k_B, with k_B being the Boltzmann constant. This means as the temperature increases, the kinetic energy increases proportionally, maintaining the same gradient.

[Generated by AI]

As this graph is a **straight line through the origin**, you can see that the kinetic energy of the particles of a substance is directly proportional to the temperature of the substance. The equation of a straight line through the origin is $y = mx$, so in this case $E_{\mathrm{k}} = mT$. The gradient, m, for this graph for any gas is always $\frac{3}{2}k_{\mathrm{B}}$, where k_{B} is the Boltzmann constant.

From this, you can infer that the absolute temperature of a substance is dependent on the average kinetic energy of its particles. The average kinetic energy of each particle can be calculated using the following equation:

Table 1. Calculating average kinetic energy of particles.

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Equation	Symbols	Units
$\bar{E}_\mathrm{k} = \frac{3}{2}k_\mathrm{B}T$	$\bar{E}_\mathrm{k}$ = average kinetic energy of molecules	joules (J)
	k_B = Boltzmann constant	$1.38 \times 10^{-23}\ \mathrm{J\ K^{-1}}$ (given in section 1.6.3 (/study/app/math-aa-hl/sid-423-cid-762593/book/fundamental-constants-id-45155/) of the DP physics data booklet)
	T = absolute temperature	kelvin (K)

Worked example 2

Calculate the average kinetic energy of the molecules of helium gas in a balloon at a temperature of 22 °C.

Solution steps	Calculations
Step 1: write out the values given in the question and convert the values to the units required for the equation	$T = 22\ ^\circ\mathrm{C}$ $T(\mathrm{K}) = T(^\circ\mathrm{C}) + 273$ $= 22 + 273$ $= 295\ \mathrm{K}$
Step 2: write out the equation	$\bar{E}_\mathrm{k} = \frac{3}{2}k_\mathrm{B}T$
Step 3: substitute the values given	$= \frac{3}{2} \times 1.38 \times 10^{-23} \times 295$
Step 4: state the answer with appropriate units and the number of significant figures used in rounding	$= 6.1065 \times 10^{-21}\ \mathrm{J} = 6.1 \times 10^{-21}\ \mathrm{J}\ \ (2\ \mathrm{s.f.})$

Try the following activity to check your understanding of temperature scales.

Activity

- **IB learner profile attribute:** Knowledgeable

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- **Approaches to learning:** Thinking skills — Reflecting at all stages of the assessment and learning cycle
- **Time required to complete activity:** 20 minutes
- **Activity type:** Individual activity

Download the worksheet and complete the practice questions. Remember to show your working. You can check your answers on the last page.

Worksheet (https://d3vrb2m3yrmyfi.cloudfront.net/media/edusys_2/content_uploads/Physics B.1.2 ACTIVITY Temperature scales.ef521260d9c2260898b4.pdf)

6 section questions

Question 1

SL HL Difficulty:

True or false?

To convert from degrees Celsius to kelvin, subtract 273.

False ✓

Accepted answers

False, F, false, f

Explanation

To convert from degrees Celsius to kelvin, add 273.

Question 2

SL HL Difficulty:

Particles of a gas at 450 °C have a kinetic energy of 1.5 × 10^{-20} J. At what temperature would the particles have double the kinetic energy?

1 1200 °C ✓

2 230 °C

3 900 °C

4 1400 °C

Explanation

First, convert the temperature to kelvin.

$$T = 450\,^{\circ}\mathrm{C}$$

Student
view

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$$\begin{aligned} T(\mathrm{K}) &= T(^\circ\mathrm{C}) + 273 \\ &= 450 + 273 \\ &= 723\ \mathrm{K} \end{aligned}$$

As the mean kinetic energy of the particles is directly proportional to the absolute temperature of the gas, if the kinetic energy doubles, the absolute temperature will also double:

$$\begin{aligned} T &= 2 \times 723 \\ &= 1446\ \mathrm{K} \end{aligned}$$

This temperature is then converted back to °C.

$$\begin{aligned} T(^\circ\mathrm{C}) &= T(\mathrm{K}) - 273 \\ &= 1446 - 273 \\ &= 1173\,^\circ\mathrm{C} \\ &= 1200\,^\circ\mathrm{C}\ (2\ \mathrm{s.f.}) \end{aligned}$$

Question 3

SL HL Difficulty:

Iron melts at 1540 °C. Convert this temperature to K. Give your answer to an appropriate number of significant figures.

The temperature is 1 1810 ✓ K.

Accepted answers and explanation

#1 1810

1,810

General explanation

$$\begin{aligned} \text{temperature (K)} &= \text{temperature } (^\circ\mathrm{C}) + 273 \\ &= 1540 + 273 \\ &= 1813\ \mathrm{K} \\ &= 1810\ \mathrm{K}\ (3\ \mathrm{s.f.}) \end{aligned}$$

Question 4

SL HL Difficulty:

Calculate the absolute temperature of hydrogen molecules with an average kinetic energy of 1.2×10^{-19} J. Give your answer to an appropriate number of significant figures.

The absolute temperature of the hydrogen molecules is 1 5800 ✓ K.

Student view

Accepted answers and explanation

Overview
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#1 5800
5,800
5800K
5800 K

General explanation

$$\bar{E}_{\mathrm{k}} = 1.2 \times 10^{-19}\ \mathrm{J}$$

$$\bar{E}_{\mathrm{k}} = \frac{3}{2} k_{\mathrm{B}} T$$

$$\begin{aligned} T &= \frac{2\bar{E}_{\mathrm{k}}}{3k_{\mathrm{b}}} \\ &= \frac{2 \times 1.2\ \times 10^{-19}}{3 \times 1.38 \times 10^{-23}} \\ &= 5797 \\ &= 5800\ \mathrm{K}\ (2\ \mathrm{s.f.}) \end{aligned}$$

Solution Steps	Calculations
Step 1: write out the values given in the question	$\bar{E}_{\mathrm{k}} = 1.2 \times 10^{-19}\ \mathrm{J}$
Step 2: write out the equation	$\bar{E}_{\mathrm{k}} = \frac{3}{2} k_{\mathrm{B}} T$
Step 3: rearrange the equation to make T the subject	$T = \frac{2\bar{E}_{\mathrm{k}}}{3k_{\mathrm{b}}}$
Step 4: substitute the values given	$= \frac{2 \times 1.2\ \times 10^{-19}}{3 \times 1.38 \times 10^{-23}}$
Step 5: state the answer with appropriate units	$T = 5797\ \mathrm{K}$ The answer should be quoted to 2 significant figures as this is the minimum number of significant figures in the question. $T = 5800\ \mathrm{K}$

Question 5

SL HL Difficulty:

Calculate the average kinetic energy of carbon dioxide molecules at a temperature of 6.0 °C.

1 5.8×10^{-21} J ✓

2 3.8×10^{-21} J

3 1.2×10^{-22} J

4 5.6×10^{-21} J

Explanation

$T = 6.0\ ^{\circ}\mathrm{C}$

Student view

Overview
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$$\begin{aligned} T(\mathrm{K}) &= T(^{\circ}\mathrm{C}) + 273 \\ &= 6.0 + 273 \\ &= 279\ \mathrm{K} \end{aligned}$$

$$\bar{E}_{\mathrm{k}} = \frac{3}{2}k_{\mathrm{B}}T$$

$$\begin{aligned} \bar{E}_{\mathrm{k}} &= \frac{3}{2}k_{\mathrm{B}}T \\ &= \frac{3}{2} \times 1.38 \times 10^{-23} \times 279 \\ &= 5.7753 \times 10^{-21} \\ &= 5.8 \times 10^{-21}\ \mathrm{J}\ (2\ \text{s.f.}) \end{aligned}$$

Question 6

SL HL Difficulty:

Particles of a gas at 450 °C have a mean velocity of v ms^{-1}. At what absolute temperature would the particles have a mean velocity of $2v$ ms^{-1}?

1 2900 K ✓

2 1000 K

3 2800 K

4 1400 K

Explanation

We know that $\bar{E}_{\mathrm{k}} = \frac{3}{2}k_{\mathrm{B}}T$ and, from section A.3, we also know that $E_{\mathrm{k}} = \frac{1}{2}mv^2$.

We can equate these two equations to find the relationship between the absolute temperature of a substance and the velocity of its particles:

$$\frac{1}{2}mv^2 = \frac{3}{2}k_{\mathrm{B}}T$$

$$T_1 = 450\ ^{\circ}\mathrm{C}$$

$$v_1 = v\ \mathrm{ms}^{-1}$$

$$\begin{aligned} T(\mathrm{K}) &= T(^{\circ}\mathrm{C}) + 273 \\ &= 450 + 273 \\ &= 723\ \mathrm{K} \end{aligned}$$

$\bar{E}_{\mathrm{k}} = \frac{3}{2}k_{\mathrm{B}}T$ and $E_{\mathrm{k}} = \frac{1}{2}mv^2$

Equate these equations to find the relationship between the absolute temperature of a substance and the velocity of its particles:

$$\frac{1}{2}mv^2 = \frac{3}{2}k_{\mathrm{B}}T$$

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$$v^2 = \frac{3k_B T}{m}$$

Remove $\frac{3k_B}{m}$ to find that:

$$v^2 \propto T$$

v^2 is directly proportional to T

If v increases by a factor, T increases by the square of the same factor. In this case, v increased by a factor of 2 so T must increase by a factor of 4.

$$\begin{aligned} T_2 &= 723 \times 4 \\ &= 2892 \\ &= 2900 \text{ K} \ \ (2 \text{ s.f.}) \end{aligned}$$

Solution Steps	Calculations
Step 1: Write out the values given in the question	$T_1 = 450\ ^\circ\text{C}$ $v_1 = v \text{ ms}^{-1}$
Step 2: Convert the values to the units required for the equation	$\begin{aligned} T(\text{K}) &= T(^\circ\text{C}) + 273 \\ &= 450 + 273 \\ &= 723 \text{ K} \end{aligned}$
Step 3: Write out the equations	$\bar{E}_k = \frac{3}{2} k_B T$ $E_k = \frac{1}{2} m v^2$
Step 4: As both of these equations give us the kinetic energy of the particles in the gas, we can equate the equations	$\frac{1}{2} m v^2 = \frac{3}{2} k_B T$
Step 5: Rearrange the equation to make velocity the subject	$v^2 = \frac{3k_B T}{m}$
Step 6: Remove the constants to find the relationship	Remove $\frac{3k_B}{m}$ to find that: $v^2 \propto T$ v^2 is directly proportional to T
Step 7: Rearrange the equation to make T the subject	$T \propto v^2$

Student view

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Solution Steps	Calculations
Step 8: Think about what this means	If v increases by a factor, T increases by the square of the same factor. In this case, v increased by a factor of 2 so T must increase by a factor of 4.
Step 9: Multiply the original temperature in kelvin by the scale factor	$T_2 = 723 \times 4$
Step 10: State the answer with appropriate units	$T = 2892$ Answer should be quoted to 2 significant figures as this is the minimum number of significant figures in the question. $T = 2900\text{ K}$

B. The particulate nature of matter / B.1 Thermal energy transfers

Changing temperature and changing phase

B.1.7: Temperature difference and direction of resultant thermal energy transfer B.1.8: Phase changes
B.1.9: Quantitative analysis of thermal energy transfers

Learning outcomes

By the end of this section you should be able to:

- Use graphs and calculations to describe what happens to a substance as it is heated.
- Analyse heat transfers and phase changes using the concepts of specific heat capacity and specific latent heat.

The absolute temperature of a substance is a measure of the average kinetic energy of its particles (see section B.1.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/temperature-scales-id-44050/)). What do you think happens to the average kinetic energy of the particles of a substance, and therefore the absolute temperature of the substance, when:

1. the substance is heated, but it does not change state?
2. the substance is heated, and it changes state?

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Can you represent your ideas as a line graph of temperature (y-axis) against time the substance is heated for (x-axis)?

Specific heat capacity

Specific heat capacity is the amount of energy required to increase the temperature of 1 kg of a substance by 1 K. It can also be thought of as the amount of energy released by 1 kg of a substance when its temperature decreases by 1 K.

Different materials have different specific heat capacities but, whether there is 1×10^6 kg of a substance or 1 milligram, if it is the same material then its specific heat capacity will be the same.

For example, the specific heat capacity of copper is 385 J kg^{-1} K^{-1}. This means that to increase the temperature of 1 kg of copper by 1 K, 385 J of energy needs to be supplied.

Try the following examples to check your understanding.

Worked example 1

How much energy is required to increase the temperature of 2 kg of copper by 1 K?

770 J

As the mass of copper doubles, the energy required to increase its temperature by 1 K also doubles.

Worked example 2

How much energy is required to increase the temperature of 1 kg of copper by 2 K?

Solution: 770 J

As the change in temperature doubles, the energy required to increase its temperature by 1 K also doubles.

The energy required can be calculated using the following equation:

Table 1. Calculating the energy stored or released as a substance's temperature changes.

Student view

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Equation	Symbols	Units
$Q = mc\Delta T$	Q = energy	joule (J)
	m = mass of substance to be heated	kilogram (kg)
	c = specific heat capacity	joules per kilogram per kelvin (J kg^{-1} K^{-1})
	ΔT = change in temperature	degrees Celsius or kelvin (°C or K)

Study skills

Remember that, as a temperature change of 1°C is the same as a temperature change of 1 K, it is not necessary to convert initial and final temperatures in °C to K before substituting them into the equation.

Worked example 3

Calculate the energy that must be supplied to heat 250 g of water from 19 °C to 92 °C.

Specific heat capacity of water = 4200 J kg^{-1} K^{-1}

Solution steps	Calculations
Step 1: write out the values given in the question and convert the values to the units required for the equation	$T_1 = 19\ ^\circ\mathrm{C}$ $T_2 = 92\ ^\circ\mathrm{C}$ $m = 250\ \mathrm{g} = 250\times10^{-3}\ \mathrm{kg}$ $c = 4200\ \mathrm{J\ kg^{-1}\ K^{-1}}$
Step 2: write out the equation	$Q = mc\Delta T$
Step 3: substitute the values given	$= \left(250 \times 10^{-3}\right) \times 4200 \times (92 - 19)$
Step 4: state the answer with appropriate units and the number of significant figures used in rounding	$= 76\,650\ \mathrm{J}$ $= 77\,000\ \mathrm{J}$ or $77\ \mathrm{kJ}$ (2 s.f.)

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Study skills

When investigating specific heat capacity, the following assumptions are often made:

- The specific heat capacity of the container is negligible, meaning that none of the energy supplied is used to increase the temperature of the container.
- The container is perfectly insulated, meaning that there is no heat lost to the environment.

When two substances at different temperatures are mixed, thermal energy is transferred from the hotter substance to the colder substance. The amount of energy leaving the hotter substance must be the same as the amount of energy being absorbed by the colder substance, so that energy is conserved (see section A.3.2a (/study/app/math-aa-hl/sid-423-cid-762593/book/conservation-of-energy-id-43085/)). In real-life scenarios, some energy is also transferred to the surroundings, so that the sum of this 'lost' energy and the energy absorbed by the colder substance is always equal to the energy leaving the hotter substance. In most calculation-based questions, you can assume that all the energy leaving the hotter substance will be absorbed by the colder substance and will therefore contribute to its temperature increase.

Worked example 4

A cube of copper of mass 0.072 kg is heated to a temperature of 970 °C in a bunsen burner flame, and then plunged into 920 g of water at 18 °C. Show that the equilibrium temperature of the copper cube and the water is approximately 25 °C.

Specific heat capacity of copper = 385 J kg^{-1} K^{-1}

Specific heat capacity of water = 4200 J kg^{-1} K^{-1}

Solution steps	Calculations
Step 1: write out the values given in the question and convert the values to the units required for the equation	$m_{\text{c}} = 0.072 \text{ kg}$ $T_{\text{ic}} = 970\ ^\circ\text{C}$ $c_{\text{c}} = 385 \text{ J kg}^{-1} \text{ K}^{-1}$ $m_{\text{w}} = 920 \text{ g} = 0.92 \text{ kg}$ $T_{\text{iw}} = 18\ ^\circ\text{C}$ $c_{\text{w}} = 4200 \text{ J kg}^{-1} \text{ K}^{-1}$ As you are calculating change in temperature, it is not necessary to convert the temperatures from °C to K.

Student view

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Solution steps	Calculations
Step 2: write out the equation	energy transferred from copper = energy transferred to water $m_c c_c (T_{ic} - T_f) = m_w c_w (T_f - T_{iw})$
Step 3: substitute the values given	$0.072 \times 385\,(970 - T_f) = 0.92 \times 4200\,(T_f - 18)$
Step 4: multiply out brackets, add $27.72T_f$ to both sides and add 69552 to both sides	Multiply out brackets: $26\,888.4 - 27.72T_f = 3864T_f - 69\,552$ Add $27.72T_f$ to both sides: $26\,888.4 = 3891.72T_f - 69\,552$ Add 69 552 to both sides: $96\,440.4 = 3891.72T_f$
Step 5: rearrange to make T_f the subject of the equation	$T_f = \frac{96\,440.4}{3891.72}$
Step 6: state the answer with appropriate units and compare this value to the value given in the question	$= 24.781\ ^\circ C = 25\ ^\circ C$ (2 s.f.) This is comparable to the value of $\approx 25\ ^\circ C$ given in the question.

Study skills

Section Student... (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/temperature-scales-id-44050/print/) Assign

When given a 'show that' question:

1. Never **start** with the number given. You should carry out the calculation as normal and your final answer should be the value given by the question.
2. Always give your final answer to at least one more significant figure than the value you are given, **then** round it to the same number. This demonstrates that you have calculated the final answer yourself, not just taken it from the question.

Phase change

A phase change occurs when a substance changes from one phase to another, for example, from solid to liquid.

Student view

Use **Interactive 1** to check your understanding of changes of phase.

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Interactive 1. Label the Diagram With the Correct Changes of Phase.

More information for interactive 1

This is a drag and drop activity designed to help users understand the changes of state between solids, liquids, and gases. The visual shows three particle diagrams representing the three states of matter: solid on the left, liquid at the center, and gas on the right. Each state is labeled accordingly with the tags “Solid”, “Liquid”, and “Gas” beneath the illustrations of the particles.

For the “Solid” labeled diagram, particles are tightly packed in a fixed, orderly arrangement, indicating a rigid structure with little movement. For the “Liquid” labeled diagram, particles are close together but randomly arranged, showing that they can slide past one another while remaining in contact. For the “Gas” labeled diagram, particles are widely spaced and move freely in all directions, representing high-energy, dispersed motion.

Between each state are double-sided green arrows indicating reversible physical changes. Below the green arrows and between each state, there are blank spaces where users are required to drag and drop the appropriate phase change labels.

Below the diagram, there are four draggable labels: “Freezing or solidifying”, “Condensing”, “Melting”, and “Evaporation or boiling”. The user must drag and drop each label into the correct blank space. Once all the labels are placed correctly, the user can press the Check button to confirm their answers.

Read below for solution:

From Solid to Liquid: Melting.

From Liquid to Solid: Freezing or solidifying.

From Liquid to Gas: Evaporation or boiling.

Student
view

From Gas to Liquid: Condensing.

This activity visually reinforces the concept of reversible physical changes and helps users link particle behavior to phase transition terminology.

Nature of Science

Scientists can use common physical properties, such as the density of a substance, to identify and compare substances. How do physical quantities, such as the melting and boiling point of a substance, allow scientists to identify substances and compare their purity?

When a substance remains in the **same phase** and is heated, the energy supplied is transferred to the kinetic energy of the particles, thus increasing the temperature of the substance.

During a **change of phase**, all of the energy supplied is transferred to the potential energy of the particles and not kinetic energy. For this reason, all of the energy supplied provides the particles with more energy to overcome the intermolecular forces of attraction between them. This allows them to move further apart, and the volume of the substance expands. For this reason, during a change of phase, the **temperature of the substance remains constant**. This is shown by the graph in **Figure 1**.

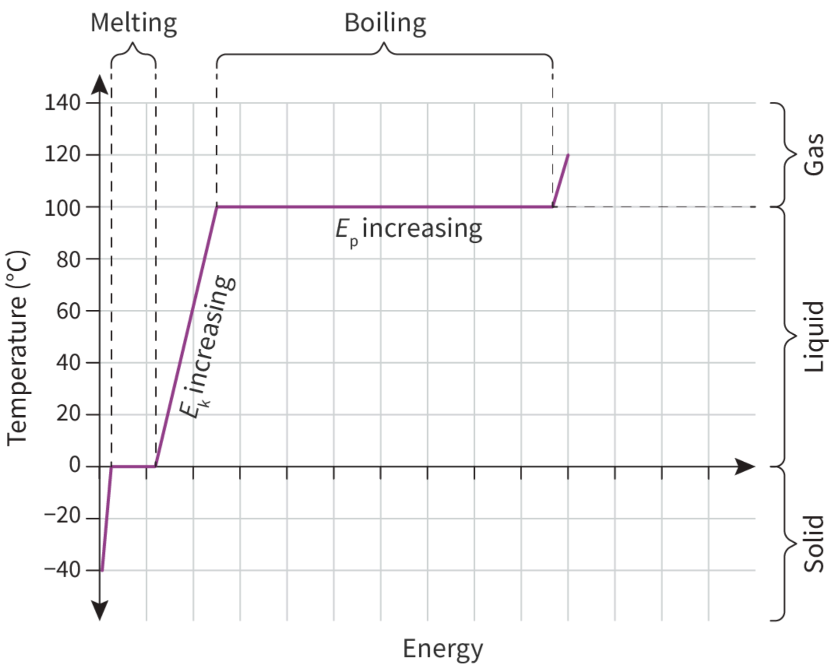


Figure 1. Graph of temperature against time (or energy supplied).

More information for figure 1

Overview
(/study/app/math-aa-hl/sid-423-cid-762593/c

The graph depicts the relationship between temperature and energy supplied during phase changes. The X-axis represents energy, and the Y-axis represents temperature in degrees Celsius. The graph begins with a decreasing curve starting at -40°C, indicating a solid state. As energy increases, the temperature rises steeply to 0°C, marking the melting point. During this phase, the substance transitions from solid to liquid. The curve levels off, showing a constant temperature of 0°C while energy is still being supplied, illustrating the phase change from solid to liquid.

The next segment involves another increase in temperature up to 100°C in the liquid phase. Upon reaching 100°C, the temperature remains constant while energy continues to increase, representing the boiling phase change where the substance goes from liquid to gas. Above 100°C, the energy continues to increase as the temperature gradually rises, indicating the gaseous state. The labels E_k (kinetic energy) and E_p (potential energy) on the graph indicate where these energies increase as the phase changes occur.

[Generated by AI]

What do you think is the significance of:

- the gradient of the line when the substance is in the same phase and its temperature is increasing?
- the line being horizontal when the substance is changing phase at constant temperature?

As you can see in **Figure 1**, when the substance is in the same phase and its temperature increases, the graph shows a linear relationship with positive correlation. During a change of phase, the graph is a straight horizontal line, showing that although more energy is being supplied, the temperature does not change. This is because all of the energy supplied increases the potential energy.

Specific latent heat

During a phase change, the equation for specific heat capacity does not apply, as there is no change in temperature. To calculate the energy required to change the phase of a substance, we must use the concept of specific latent heat, which is the amount of energy required to change the phase of 1 kg of a substance at constant temperature.

Specific latent heat of fusion, L_f: the amount of energy required to change the phase of 1 kg of a substance at constant temperature from solid to liquid.

Specific latent heat of vaporisation, L_v: the amount of energy required to change the phase of 1 kg of a substance at constant temperature from liquid to gas.

Student view

The energy required can be calculated using the equation:

Overview
(/study/app/math-aa-hl/sid-423-cid-762593/c

Table 2. Calculating the energy required to change state.

Equation	Symbols	Units
$Q = mL$	Q = energy	joule (J)
	m = mass of substance to be heated	kilogram (kg)
	L = specific latent heat of fusion or vaporisation	joules per kilogram (J kg^{-1})

Worked example 5

In order to make a gold ring, 1.6 g of gold is melted.

Calculate the energy that must be supplied.

Specific latent heat of fusion of gold = 63 000 J kg^{-1}

Solution steps	Calculations
Step 1: write out the values given in the question and convert the values to the units required for the equation	$m = 1.6\text{ g} = 1.6 \times 10^{-3}\text{ kg}$ $L_\text{f} = 63\,000\text{ J kg}^{-1}$
Step 2: write out the equation	$Q = mL$
Step 3: substitute the values given	$= (1.6 \times 10^{-3}) \times 63\,000$
Step 4: state the answer with appropriate units and the number of significant figures used in rounding	$= 100.8 = 100\text{ J (2 s.f.)}$

Worked example 6

A small steam engine with a power rating of 1200 W is used to boil 220 g of water at 100 °C.

Calculate the time taken to boil all of the water.

Specific latent heat of vaporisation of water = 2.26 × 10^{6} J kg^{-1}

Student view

Overview
(/study/app/math-aa-hl/sid-423-cid-762593/c

Solution steps	Calculations
Step 1: write out the values given in the question and convert the values to the units required for the equation	$P = 1200\text{ W}$ $m = 220\text{ g} = 0.22\text{ kg}$ $L_\text{v} = 2.26\times10^6\text{ J kg}^{-1}$
Step 2: write out the relevant equations	$P = \frac{\Delta W}{\Delta t}$ so $\Delta W = P\Delta t$ and $Q = mL_\text{v}$ As work done is equal to energy transferred, the two equations can be equated: $P\Delta t = mL_\text{v}$
Step 3: rearrange the equation to make Δt the subject	$\Delta t = \frac{mL_\text{v}}{P}$
Step 4: substitute the values given	$= \frac{0.22\times2.26\times10^6}{1200}$
Step 5: state the answer with appropriate units and the number of significant figures used in rounding	$= 414\text{ seconds} = 410\text{ seconds (2 s.f.)}$

Let's look at an example that involves specific heat capacity and specific latent heat, for example, putting ice cubes into a drink at room temperature. Although the drink is cold, its temperature is greater than the temperature of the ice, so thermal energy is transferred from the drink to the ice. This results in the temperature of the drink decreasing. The ice cubes go through more changes:

- While the ice is a solid, its temperature increases to its melting point, in this case, 0 °C.
- The ice cube melts at constant temperature as all of the energy transferred from the drink is used to increase the potential energy of the particles in the ice cube.
- Now the ice cube is a liquid and its temperature increases until the drink and the liquid ice cubes are in thermal equilibrium.

This process is shown in °C.

Student view

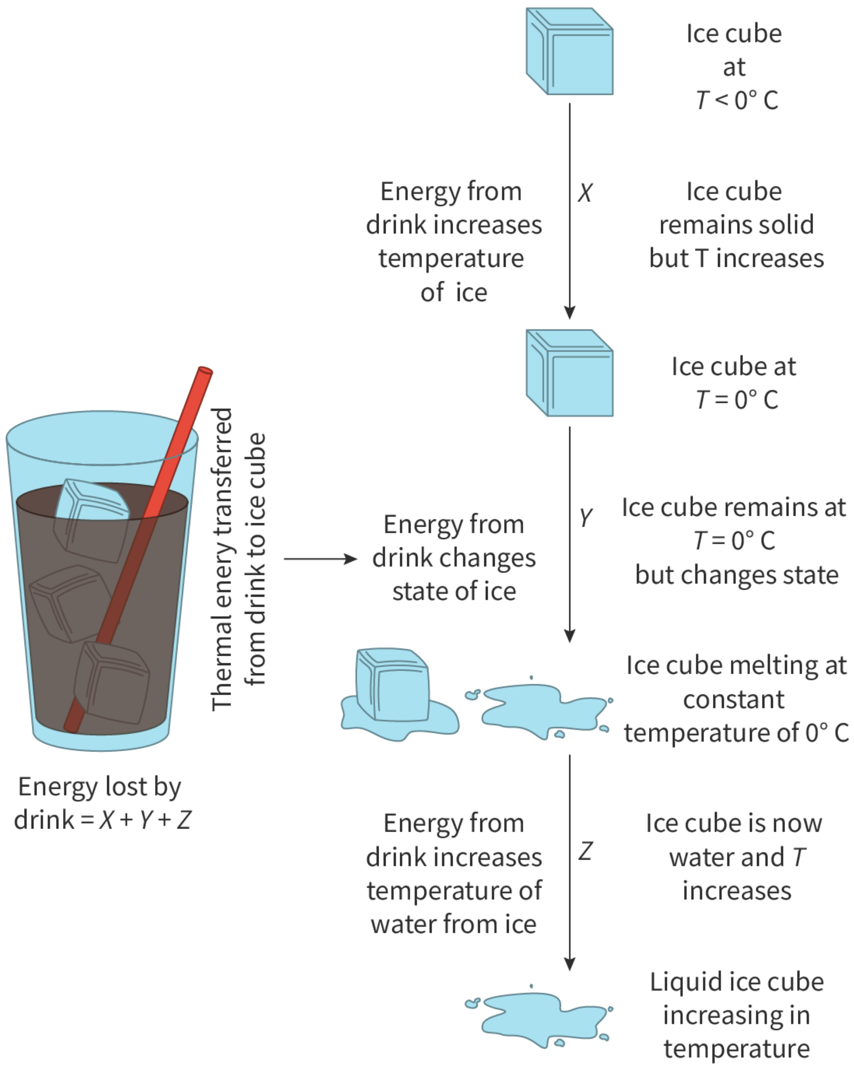


Figure 2. Temperature changes as ice melts in a drink.

More information for figure 2

This diagram illustrates the stages of ice melting in a drink and the associated thermal energy changes. The process starts with an ice cube in a drink, represented by a glass with a straw and several cubes of ice. The image is divided into three main vertical sections labeled as X, Y, and Z, connected by arrows to indicate the sequence of events.

In the X stage, the ice cube is depicted at a temperature below 0°C. The text reads, "Energy from drink increases temperature of ice," indicating that the ice absorbs heat from the drink. As a result, the ice cube remains solid, and its temperature increases.

The Y stage represents the ice at 0°C. Here, the energy from the drink causes the ice cube to change state while remaining at the same temperature. This is shown as the transition from solid ice to melting ice at 0°C, labeled as "Ice cube remains at T = 0°C but changes state."

Finally, in the Z stage, the energy from the drink increases the temperature of the water formed from the melted ice. The text notes that the "liquid ice cube increases in temperature," as it absorbs more energy, resulting in a warmer liquid state.

Student
view

Overall, the diagram effectively illustrates the flow of energy from the drink to the ice throughout each stage of melting and temperature change.

[Generated by AI]

This process is demonstrated in the following worked example.

Worked example 7

In a perfectly insulated container, a 25 g ice cube at 260 K is placed into a cup of 120 g of water at 300 K.

What is the final temperature of the mixture?

Specific heat capacity of ice = 2100 J kg^{-1} K^{-1}

Specific heat capacity of water = 4200 J kg^{-1} K^{-1}

Specific latent heat of fusion of water = 330 000 J kg^{-1}

Solution steps	Calculations
Step 1: write out the values given in the question and convert the values to the units required for the equation	$m_{\mathrm{i}} = 25\ \mathrm{g} = 0.025\ \mathrm{kg}$ $T_{\mathrm{ii}} = 260\ \mathrm{K}$ $m_{\mathrm{w}} = 120\ \mathrm{g} = 0.120\ \mathrm{kg}$ $T_{\mathrm{iw}} = 300\ \mathrm{K}$ $c_{\mathrm{i}} = 2100\ \mathrm{J\ kg^{-1}\ K^{-1}}$ $c_{\mathrm{w}} = 4200\ \mathrm{J\ kg^{-1}\ K^{-1}}$ $L_{\mathrm{fw}} = 330\,000\ \mathrm{J\ kg^{-1}}$
Step 2: write out the equation	energy transferred from water = energy transferred to ice energy transferred from water = energy to increase temperature of ice + energy to melt ice + energy to increase temperature of liquid ice $m_{\mathrm{w}}c_{\mathrm{w}}(T_{\mathrm{iw}} - T_{\mathrm{f}}) = m_{\mathrm{i}}c_{\mathrm{i}}(T_{\mathrm{fi}} - T_{\mathrm{ii}}) + m_{\mathrm{i}}L_{\mathrm{fw}} + m_{\mathrm{i}}c_{\mathrm{w}}\left(T_{\mathrm{f}} - T_{\mathrm{melted\ i}}\right)$

Overview
(/study/app/math-aa-hl/sid-423-cid-762593/c

Solution steps	Calculations
Step 3: substitute the values given	$0.12 \times 4200\,(300 - T_\text{f}) = 0.025 \times 2100\,(273 - 260) + 0.025 \times 330\,000 + 0.025 \times 4200\,(T_\text{f} - 273)$
Step 4: multiply out the brackets, add $504T_\text{f}$ to both sides and add 27982.5 to both sides	Multiply out the brackets: $151\,200 - 504T_\text{f} = 682.5 + 8250 + 105T_\text{f} - 28\,665$ $151\,200 - 504T_\text{f} = 105T_\text{f} - 19\,732.5$ Add $504T_\text{f}$ to both sides: $151\,200 = 609T_\text{f} - 19\,732.5$ Add $19\,732.5$ to both sides: $170\,932.5 = 609T_\text{f}$
Step 5: rearrange the equation to find T_f	$T_\text{f} = \dfrac{170\,932.5}{609}$
Step 6: state the answer with appropriate units and the number of significant figures used in rounding	$T_\text{f} = 280.68$ $= 280\text{ K }(2\text{ s.f.})$

Try the following activity to check your understanding of phase changes.

Activity

- **IB learner profile attribute:** Knowledgeable
- **Approaches to learning:** Thinking skills — Reflecting at all stages of the assessment and learning cycle
- **Time required to complete activity:** 20 minutes
- **Activity type:** Individual activity

Download the worksheet and complete the practice questions. Remember to show your working. You can check your answers on the last page.

Worksheet (https://d3vrb2m3yrmyfi.cloudfront.net/media/edusys_2/content_uploads/Physics B.1.3 ACTIVITY Changing temperature and changing phase.544262eaf293279083a4.pdf)

Student view

Overview
(/study/app/math-aa-hl/sid-423-cid-762593/c

6 section questions

Question 1

SL HL Difficulty:

True or false?

When a substance changes phase, there is no change in temperature.

True

Accepted answers

True, T, true, t

Explanation

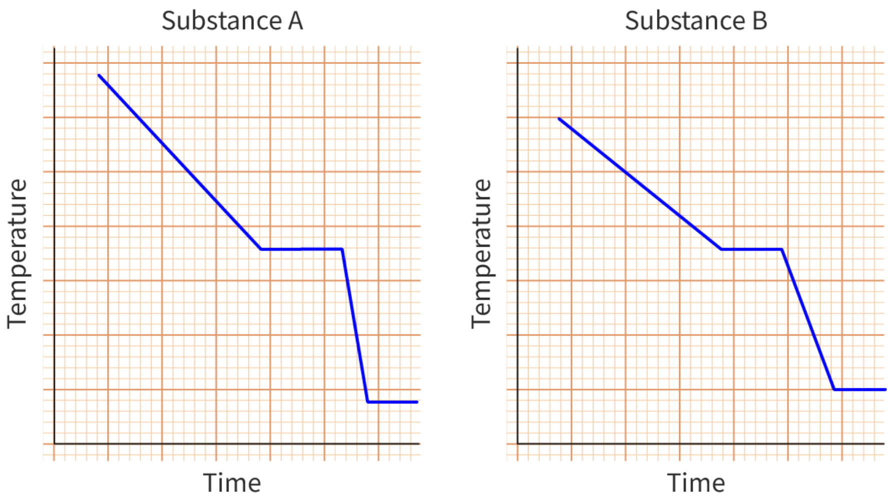
When a substance changes phase, there is no change in temperature because all of the energy supplied is being used to weaken or strengthen the forces of attraction between the molecules.

Question 2

SL HL Difficulty:

The graphs show the cooling curves of two different substances, A and B.

Which substance has a larger specific latent heat of vaporisation?



More information

A

Accepted answers

A, Substance A

Explanation

Student view

Overview
(/study/app/math-aa-hl/sid-423-cid-762593/c

The specific latent heat of vaporisation is associated with the first horizontal part of the graph. The longer this line, the greater the amount of energy that needs to be supplied to change the phase of the substance from liquid to gas and, therefore, the greater the specific latent heat of vaporisation.

Question 3

SL HL Difficulty:

Calculate the energy required to increase the temperature of 2.4 kg of water from 72 °C to 80 °C. Give your answer to an appropriate number of significant figures.

Specific heat capacity of water = 4200 J kg^{-1} K^{-1}

The energy required is 1 81000 ✓ J.

Accepted answers and explanation

#1 81000

81,000

81 000

81000 J

81000J

81kJ

81 kJ

General explanation

$T_1 = 72\ ^\circ\mathrm{C}$

$T_2 = 80\ ^\circ\mathrm{C}$

$m = 2.4\ \mathrm{kg}$

$c = 4200\ \mathrm{J\ kg^{-1}\ K^{-1}}$

$$
\begin{aligned}
Q &= mc\Delta T \\
&= mc(T_2 - T_1) \\
&= 2.4 \times 4200 \times (80 - 72) \\
&= 80\,640 \\
&= 81\,000\ \mathrm{J}\ (2\ \mathrm{s.f.})
\end{aligned}
$$

Question 4

SL HL Difficulty:

4.2 kg of ice at a temperature of −4.0 °C is heated to its melting point and then melted completely.

Calculate the energy supplied. Give your answer in MJ to an appropriate number of significant figures.

$$c_{\text{ice}} = 2100\ \mathrm{J\ kg^{-1}\ K^{-1}}$$

$$L_{\mathrm{f}} = 334\,000\ \mathrm{J\ kg^{-1}}$$

Student view

Overview
(/study/app/math-aa-hl/sid-423-cid-762593/c

The energy supplied is 1 1.4 ✓ MJ.

Accepted answers and explanation

#1 1.4

General explanation

To raise temperature of ice:

$T_1 = -4\,°\mathrm{C}$

$T_2 = 0\,°\mathrm{C}$ (because this is the melting temperature of ice)

$m = 4.2\ \mathrm{kg}$

$c = 2100\ \mathrm{J\ kg^{-1}\ K^{-1}}$

To change the phase of ice:

$m = 4.2\ \mathrm{kg}$

$L_\mathrm{f} = 334\,000\ \mathrm{J\ kg^{-1}}$

$Q = mc\Delta T + mL$

$$\begin{aligned} Q &= mc(T_2 - T_1) + mL \\ &= 4.2 \times 2100 \times (0 - (-4)) + (4.2 \times 334\,000) \\ &= 1\,438\,080 \\ &= 1\,400\,000\ \mathrm{J\ or\ 1.4\ MJ\ (2\ s.f.)} \end{aligned}$$

Question 5

SL HL Difficulty:

A student has equal masses of substances A and B. Substance A takes twice as long to melt as substance B. If the power, P, supplied to substance A is twice the power supplied to substance B, what is the ratio $\frac{L_\mathrm{f}\text{ of substance A}}{L_\mathrm{f}\text{ of substance B}}$?

1 4 ✓

2 $\frac{1}{4}$

3 $\frac{1}{2}$

4 2

Explanation

$Q = mL$

$P = \frac{Q}{t}$ which rearranges to give $Q = Pt$ which can be substituted into the equation above:

$$Pt = mL$$

If the mass is the same for both substances, it can be excluded from the equation.

Student view

$Pt = L$ which tells us that:

L is directly proportional to P

L is directly proportional to t

	Substance A	Substance B
P	$2P$	P
t	$2t$	t

$$\begin{aligned}\frac{L_\text{f}\text{ of substance A}}{L_\text{f}\text{ of substance B}} &= \frac{P_\text{A}t_\text{A}}{P_\text{B}t_\text{B}}\\ &= \frac{2P2t}{Pt}\\ &= \frac{4Pt}{Pt}\\ &= 4\end{aligned}$$

Question 6

SL HL Difficulty:

In a completely isolated system, 15 g of steam at a temperature of 120 °C floats on top of 180 g of water at a temperature of 22 °C. The steam condenses and the temperature of the water increases.

Calculate the equilibrium temperature of the system. Give your answer to an appropriate number of significant figures.

Specific heat capacity of water = 4200 J kg^{-1} K^{-1}

Specific heat capacity of steam = 2000 J kg^{-1} K^{-1}

Specific latent heat of vaporisation of water = 2.3 × 10^{6} J kg^{-1}

The equilibrium temperature of the system is 1 71 ✓ °C.

Accepted answers and explanation

#1 71

71 degrees C

General explanation

m_s = 15 g

T_{is} = 120 °C

c_s = 2000 J kg^{-1} K^{-1}

Overview (/study/app/math-aa-hl/sid-423-cid-762593/c

m_W = 180 g

T_{iw} = 22 °C

c_W = 4200 J kg^{-1} K^{-1}

L_V = 2.3 × 10^6 J kg^{-1}

m_S = 0.015 kg

m_W = 0.180 kg

It is not necessary to convert the temperatures as you are dealing with change in temperature.

Conservation of energy means:

energy transferred from steam = energy transferred to cold water

Which can be expanded to:

energy to decrease temp of steam + energy to condense steam + energy to decrease temp of hot water = energy transferred to cold water

$$
\begin{aligned}
m_s c_s\left(T_{is}-T_{fs}\right) \ + \ m_s L_s+m_s c_w\left(T_{fs}-T_f\right) &= m_w c_w(T_f-T_{iw}) \\
0.015 \times 2000(120-100)+\left(0.015 \times 2.3 \times 10^6\right)+0.015 \times 4200(100-T_f) &= 0.18 \times 4200(T_f-22) \\
600+34\,500+6300-63T_f &= 756T_f-16\,632 \\
41\,400-63T_f &= 756T_f-16\,632 \\
58\,032 &= 819T_f \\
T_f &= 70.857\,^{\circ}\mathrm{C} \\
T_f &= 71\,^{\circ}\mathrm{C}\ (\text{to 2 s.f.})
\end{aligned}
$$

B. The particulate nature of matter / B.1 Thermal energy transfers

Thermal energy transfer

B.1.7: Temperature difference and direction of resultant thermal energy transfer B.1.10: Conduction, convection and thermal radiation

B.1.11: Conduction in terms of the difference in the kinetic energy of particles B.1.12: Quantitative analysis of rate of thermal energy transfer by conduction

B.1.13: Qualitative description of thermal energy transferred by convection

Learning outcomes

By the end of this section you should be able to apply molecular theory to describe how thermal energy is transferred by conduction, convection and radiation.

To stay in the air, tiny hummingbirds flap their wings more than 50 times per second. The enormous Andean condor, which weighs over 15 kg, can fly more than 170 kilometres without flapping its wings once.

Condors use their wings to take off, and then take advantage of thermals caused by differences in the temperature of the air to soar more than 4000 metres above the Earth's surface (**Figure 1**). These thermals are called convection currents. How do you think that convection currents are formed?

Student view

Overview
(/study/app/math-aa-hl/sid-423-cid-762593/c

Figure 1. The condor can soar without using its wings.

Credit: Ricardo La Piettra / 500px, Getty Images

Thermal energy transfer

A thermal energy transfer occurs whenever there is a difference in temperature between two bodies. Thermal energy is always transferred from an area of higher temperature to an area of lower temperature, until thermal equilibrium is reached.

Study skills

The concept of rate is discussed in section A.3.3 (/study/app/math-aa-hl/sid-423-cid-762593/book/power-and-efficiency-id-43086/) in reference to power, which is the rate of energy transfer. Rate is always per unit time, so a greater rate of thermal heat transfer means that more energy is transferred per second.

Conduction

Conduction is the transfer of thermal energy between particles in direct contact. It occurs best in solids because the particles are in contact with each other.

In conduction:

Section Student... (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/changing-temperature-and-changing-phase-id-44051/print/) Assign

- Thermal energy is supplied to one part of the solid.
- This energy is transferred to the kinetic energy of the particles closest to the heat source, and they start to vibrate more.
- They collide with neighbouring particles, transferring energy to them.
- When thermal equilibrium is reached, the net energy transfer is zero.

Student view

Interactive 1 shows thermal energy transfer by conduction in a solid (non-metal).

Interactive 1. Thermal Energy Transfer by Conduction in a Solid (Non-metal).

More information for interactive 1

The animation video illustrates thermal energy transfer by conduction in a solid. It shows a row of particles, in the form of blue spheres, with one side exposed to heat. The particles closest to the heat source turn red and begin to vibrate more intensely. As they vibrate, they collide with their neighboring particles, transferring energy to them. This process continues as the energy spreads from the heated region to the cooler regions. Gradually, more particles turn red, indicating the progression of heat transfer. The video visually demonstrates how conduction works, emphasizing how thermal energy moves through direct particle interactions until equilibrium is reached.

Due to their structure, the best conductors are metals. Metals are made up of positively charged metal ions surrounded by a ‘sea’ of negatively charged electrons. The metal ions are in fixed positions, while the electrons are free to move throughout the metal. Conduction of heat in metals occurs in the same way as in non-metal solids, but energy is also transferred to the kinetic energy of the electrons. The electrons move through the metal and, when they collide with other electrons, or metal ions, they transfer kinetic energy to them.

Interactive 2 shows conduction in metals.

Interactive 2. Conduction in metals.

More information for interactive 2

The animation video demonstrates thermal conduction in metals. It features a structured arrangement of positively charged metal ions. The metal ions are surrounded by a "sea" of free-moving electrons that are negatively charged. At first, the metal ions are blue in color. The left side of the structure is exposed to heat, causing the metal ions in that region to turn red and vibrate more intensely. As they vibrate, they transfer energy to neighboring ions, eventually causing all of the metal ions to turn red. Additionally, the free electrons in the heated region gain energy and move rapidly through the structure, colliding with other electrons and metal ions. This process allows heat to spread more efficiently across the metal compared to non-metal solids. The animation visually represents how conduction in metals is enhanced by the movement of free electrons, leading to faster thermal energy transfer.

Materials that are good at transferring thermal energy by conduction are called conductors. Materials that are poor conductors are called insulators.

How effective are liquids at transferring thermal energy by conduction? Watch **Video 1** to find out. Can you use your understanding of the concept of conduction to explain your observations?

Overview
(/study/app/math-aa-hl/sid-423-cid-762593/c

Video 1. Does conduction occur in liquids?

Calculating the rate of thermal energy transfer by conduction

You can observe the process of conduction when you cook. What material would you choose to make a pan from? Why? What is the best material to make the handle of the pan from? Would you stir the food with a wooden spoon or a metal one? Why?

The rate at which thermal energy is transferred is the amount of energy transferred per unit time. Fourier's conduction law states that the rate at which thermal energy is transferred from one side of a material to the other depends on the thermal conductivity of a material, its cross-sectional area, and the difference in temperature between the hot part of the material and the cooler part of the material (known as the temperature gradient).

Thermal conductors, such as copper and iron, conduct heat much more efficiently than insulators, such as wood and air. Conductors have a higher thermal conductivity than insulators. The values of thermal conductivity of some common substances are listed in **Table 1** below.

Table 1. Thermal conductivity of different substances.

Substance	Thermal conductivity ($W\ m^{-1}\ K^{-1}$)	Conductor or insulator
Copper	400	conductor
Aluminium	240	conductor
Iron	80	conductor

Student view

Overview
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Substance	Thermal conductivity ($\text{W m}^{-1}\text{ K}^{-1}$)	Conductor or insulator
Water	0.60	insulator
Wood	0.17	insulator
Air	0.026	insulator

It is worth noting that, for metals, there is a relationship between thermal conductivity and electrical conductivity. The free electrons in metals are responsible for both thermal and electrical conduction.

The rate at which thermal energy is transferred by conduction can be calculated using the equation in **Table 2**.

Table 2. Calculating the rate of thermal energy transfer.

Equation	Symbols	Units
$\frac{\Delta Q}{\Delta t} = -kA\frac{\Delta T}{\Delta x}$	ΔQ = change in energy	joule (J)
	Δt = time taken	second (s)
	k = thermal conductivity of the material through which thermal energy is transferred	watts per metre per degree Celsius or per kelvin ($\text{W m}^{-1}\,°\text{C}^{-1}$ or $\text{W m}^{-1}\text{ K}^{-1}$)
	A = cross-sectional area of the material through which thermal energy is transferred	metres squared (m^2)
	ΔT = difference in temperature between where thermal energy is transferred from and to	degree Celsius or kelvin
	Δx = distance over which the conduction occurs	metre (m)

where:

$$\frac{\Delta Q}{\Delta t}$$

is known as the rate of thermal energy transfer and

$$\frac{\Delta T}{\Delta x}$$

Student view

Overview (/study/app/math-aa-hl/sid-423-cid-762593/c

is known as the temperature gradient.

The negative sign in the equation is important, as it shows us that thermal energy flows from hot to cold. As $\frac{\Delta T}{\Delta x} = T_{cold} - T_{hot}$ would be negative in the direction of heat flow, the sign in the equation ensures the rate of thermal energy transfer, $\frac{\Delta Q}{\Delta t}$, is a positive value.

Worked example 1

Students use a Bunsen burner to heat a copper rod of length 50 cm and diameter 10 mm. Its initial temperature is 18 °C. One end of the rod is heated to a constant temperature of 700 °C. The other end is still at 18 °C. Calculate the rate of thermal energy transfer through the rod by conduction.

Thermal conductivity of copper = 385 W m^{-1} K^{-1}

Solution steps	Calculations
Step 1: write out the values given in the question and convert the values to the units required for the equation	$\Delta x = 50\text{ cm} = 0.5\text{ m}$ $d = 10\text{ mm} = 10 \times 10^{-3}\text{ m}$ $k = 385\text{ W m}^{-1}\text{ K}^{-1}$ $T_{\text{cold}} = 18\ ^\circ\text{C}$ $T_{\text{hot}} = 700\ ^\circ\text{C}$
Step 2: calculate the area of the cylinder heat is applied to	$A = \pi r^2$ $= \pi\left(\frac{10 \times 10^{-3}}{2}\right)^2$ $= 7.854 \times 10^{-5}\text{ m}^2$
Step 3: write out the equation	$\frac{\Delta Q}{\Delta t} = -kA\frac{\Delta T}{\Delta x}$
Step 4: substitute the values given	$= -385 \times 7.854 \times 10^{-5} \times \frac{(700 - 18)}{0.5}$
Step 5: state the answer with appropriate units and the number of significant figures used in rounding	$= -41.2444 = -41\text{ J s}^{-1}\ (2\text{ s.f.})$

Student view

Overview (/study/app/math-aa-hl/sid-423-cid-762593/c

Convection

The Andean condor uses thermals to soar high above the Earth without needing to flap its wings. In physics, thermals are called convection currents.

Convection is the transfer of thermal energy due to the mass movement of molecules caused by differences in density. It occurs best in liquids and gases because the molecules can move freely.

In convection:

- Thermal energy is supplied to one part of the fluid.
- This energy is transferred to the kinetic energy of the particles closest to the heat source, and they start to move faster.
- They collide with neighbouring particles more energetically, so the particles spread further apart.
- This part of the fluid is now less dense and therefore rises. A cooler, denser, volume of particles moves into the space.
- This process repeats in a continuous cycle known as a convection current.

Figure 2 shows a convection current lifting a condor.

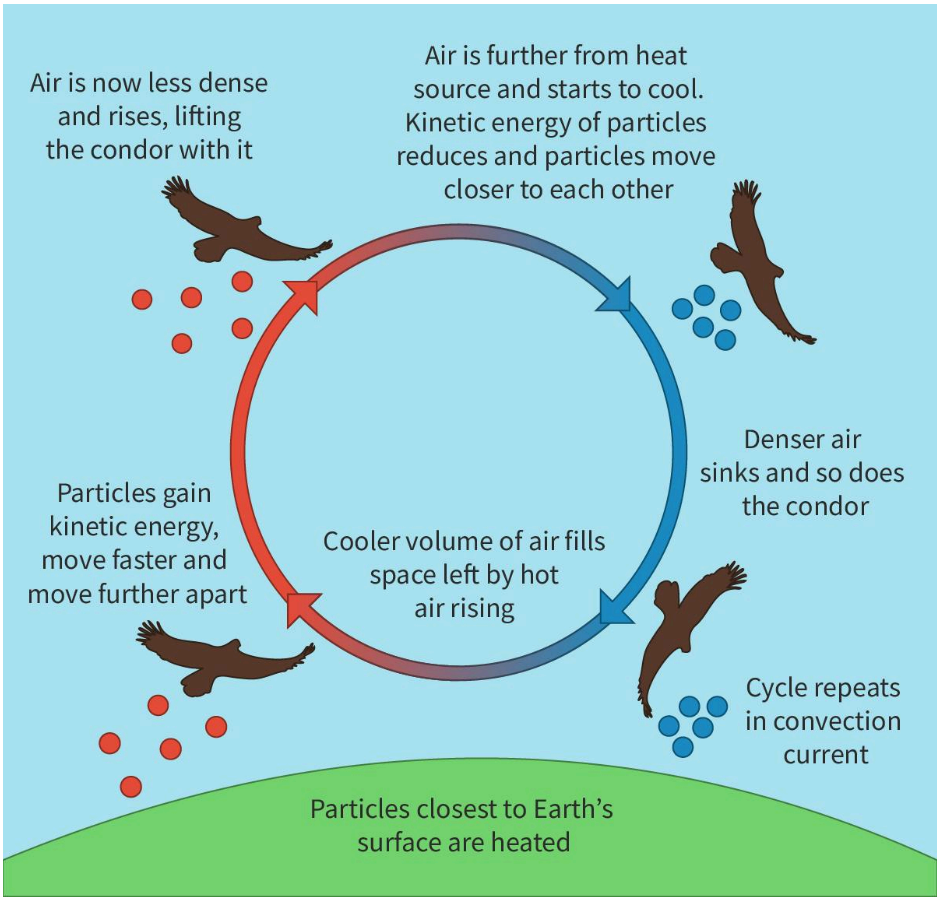


Figure 2. A convection current lifting a condor.

More information for figure 2

Student view

The image is a diagram illustrating the convection current process with a condor being lifted by the current. It shows a cycle starting at the bottom where 'Particles closest to Earth's surface are heated,' causing them to 'gain kinetic energy, move faster and move further apart.' This part of the cycle is marked with red circles and an upward arrow showing that the air becomes less dense and rises, lifting the condor with it.

At the top of the cycle, the air 'is further from heat source and starts to cool. Kinetic energy of particles reduces and particles move closer to each other,' illustrated with blue circles and a downward arrow. Here, the air becomes denser and sinks, bringing the condor down with it. This text is present with blue arrows guiding down.

The cycle continues with 'Cooler volume of air fills space left by hot air rising,' completing the convection current. The cycle repeats, showing the depicting life cycle of the warm and cool air movements illustrated along a circular path.

[Generated by AI]

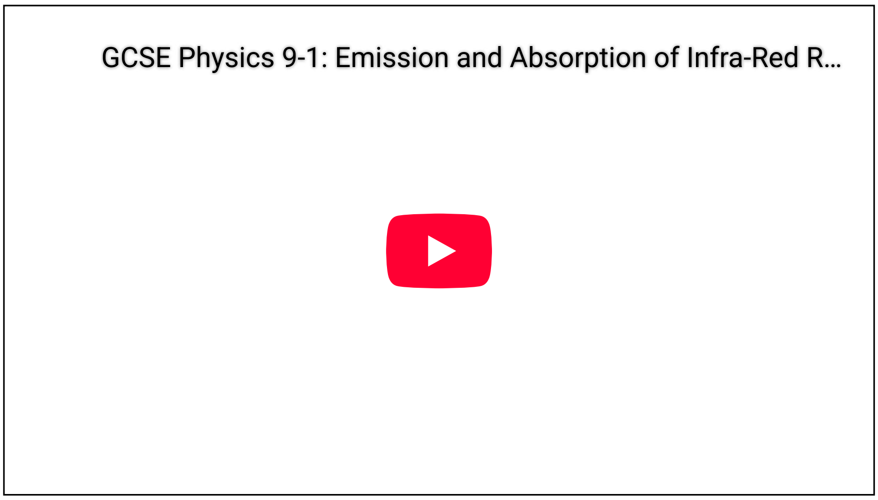
Thermal radiation

Thermal radiation is the transfer of energy by electromagnetic waves. Unlike conduction and convection, it does not need particles to travel, and can transfer energy through a vacuum.

All objects with a temperature above zero kelvin (0 K) emit thermal radiation. The greater the temperature, the higher the intensity of emitted thermal radiation.

The properties of a material affect how effective it is at absorbing, emitting or reflecting thermal radiation.

Video 2 shows some common examples of how effective different surfaces are at absorbing, emitting and reflecting infrared radiation. Watch the video then test your understanding using **Interactive 3**.



Video 2. Emission and Absorption of Infra-Red Radiation.

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Interactive 3. Energy Transfer by Different Surfaces

Creativity, activity, service

- **Strand:** Creativity
- **Learning outcome:** Demonstrate that challenges have been undertaken, developing new skills in the process

The appearance or colour of the same object can change when different wavelengths of the electromagnetic spectrum are used to create an image.

Below are two pairs of images. In each case, the image on the left is created from visible light, whereas the image on the right is created from the infrared radiation being emitted by the objects.

In photography, the different objects are at different temperatures, so they are emitting different amounts of infrared radiation. Photographers sometimes add colour afterwards to enhance the effect.

Student
view

Overview
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In astronomy, the dust of distant nebula create fabulous images in visible light, but astronomers use infrared imaging to enable them to see through the dust of a nebula cluster to study the birth of stars.

Research how different wavelengths can produce different perspectives on the same object? Examine how medical researchers or climate scientists can gain greater insight using infrared imaging to detect areas with different temperatures.

Comparison of a photograph taken in visible light and infrared light.
Source: "Human-Visible (https://commons.wikimedia.org/wiki/File:Human-Visible.jpg)" and "Human-Infrared (https://en.wikipedia.org/wiki/File:Human-Infrared.jpg)" by NASA/IPAC are in the public domain

More information

The image is a side-by-side comparison showing the same man with one photo taken with a visible light camera, and another with an infrared camera. On the left, the photograph captures him in visible light, revealing natural color and details typical of daylight photography. He is wearing transparent glasses and has a black plastic bag covering his left arm. On the right, the image shows him in infrared light, resulting in an altered view where colours range from deep purple through red, orange and yellow to white. Certain features appear transparent (such as the plastic bag, making his left arm visible), and certain features are now opaque, including his glasses.

[Generated by AI]

Student view

Comparison of an image taken in visible and infrared light by the Hubble Space Telescope.

Source: "Comparison views of 'Mystic Mountain'" by NASA/ESA/M. Livio & Hubble 20th Anniversary Team (STScI) (https://esahubble.org/images/heic1007b) is licensed under CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/)

Our understanding of how different surfaces interact with thermal radiation can lead to improved designs to help keep things cool or warm for longer periods of time. An example of this is the solar shower used by campers (**Figure 3**). A solar shower is a bag that can be filled with water and hung from a tree in order to heat up the water. The bag has a sprinkler attached, which can be opened so that a person can take a warm shower. The outside of the bag is matt black as matt black surfaces are excellent absorbers of thermal radiation, so the water inside heats up quickly.

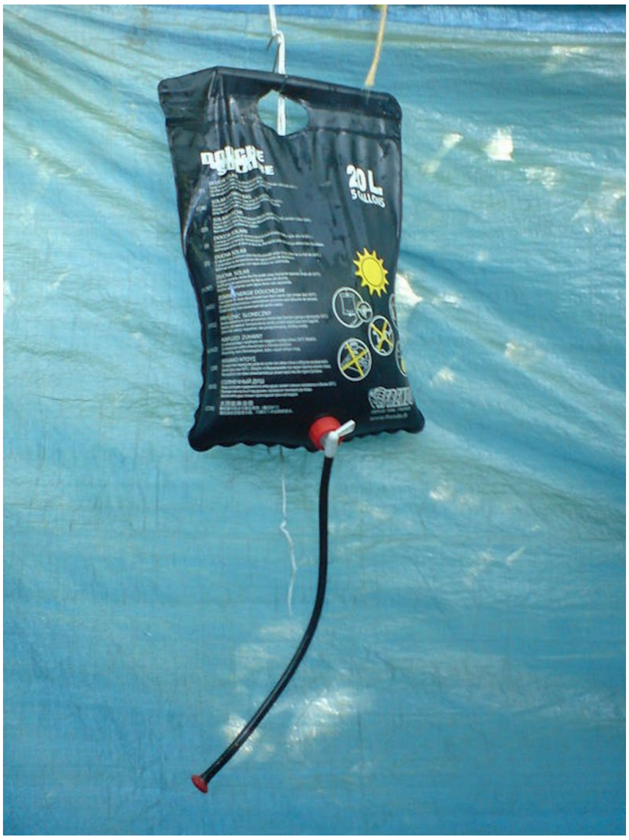

Figure 3. A solar shower.

Source: "Douche solaire (https://commons.wikimedia.org/wiki/File:Douche_solaire.jpg)" by Medjaï is in the public domain

Nature of Science

Does the word 'radiator' mean the same in physics as it does in everyday life?

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Radiator.
Credit: northlightimages, Getty Images

In everyday life, radiators are hollow metal panels filled with hot water, used to heat rooms in countries with cold climates. Alternatively, it is a device inside a car engine that helps to keep the engine cool. Use your understanding of the physics meaning of radiator to argue:

- Why **both** of these examples are radiators?
- Why **neither** of these examples is a radiator?

Video 3 shows an example of a material used by NASA scientists to protect space shuttles on re-entry to the Earth's atmosphere. How have the scientists applied the different mechanisms of thermal energy transfer in order to design these space shuttle tiles?

Video 3. The physics of space shuttle tiles.

Try the following activity to check your understanding of thermal energy transfers.

Student
view

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Activity

- **IB learner profile attribute:** Thinker
- **Approaches to learning:** Thinking skills— Applying key ideas and facts in new contexts
- **Time required to complete activity:** 40 minutes
- **Activity type:** Pair/group activity

Look at The big picture (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43777/) at the beginning of this subtopic.

With a partner, or in a small group, design a spacesuit for use by astronauts that makes use of conduction, convection and infrared radiation. The spacesuit needs to keep the astronaut cool when it is hot and warm when it is freezing.

You may want to think about:

- which materials would be most suitable and why
- the colours of the outside and inside of the suit
- how the suit could be cooled.

6 section questions

Question 1 SL HL Difficulty:

True or false?

Thermal energy always travels from areas of low temperature to areas of high temperature.

False ✓

Accepted answers

False, F, f, false

Explanation

Energy is transferred from where there is more energy to where there is less energy. Temperature is a measure of the average kinetic energy of the particles in a substance. If energy is transferred from where there is more energy to where there is less energy, this coincides with moving from an area of higher temperature to an area of lower temperature.

Question 2 SL HL Difficulty:

Student
view

Overview (/study/app/math-aa-hl/sid-423-cid-762593/c

The transfer of thermal energy by 1 Conduction ✓ is most effective in solids, while 2 convection ✓ happens best in liquids and gases. 3 Infrared ✓ is an electromagnetic wave emitted by all objects with a temperature above 0 K.

Accepted answers and explanation

#1 Conduction
conduction

#2 convection

#3 Infrared
infrared
Infra-red
Infra red
infra-red
infra red
infrared radiation
infra-red radiation

General explanation

Conduction is the transfer of thermal energy by particles in direct contact. It happens best in solids because the particles are close together and have strong intermolecular forces between them.

Convection is the transfer of thermal energy by the movement of particles. The particles must be able to move freely so it only happens in liquids and gases.

Infrared radiation is emitted by all objects with a temperature above 0 K.

Question 3

SL HL Difficulty:

Dark, matt surfaces are the best 1 emitters ✓ and 2 absorbers ✓ of infrared radiation, while light, shiny surfaces are the best 3 reflectors ✓ .

Accepted answers and explanation

#1 emitters
absorbers

#2 absorbers
emitters

#3 reflectors

Student view

General explanation

Overview (/study/app/math-aa-hl/sid-423-cid-762593/c

	Absorb	Emit	Reflect
dark matt surface	good	good	poor
light, shiny surface	poor	poor	good

Question 4

SL HL Difficulty:

Calculate the rate of thermal energy transfer through an aluminium rod of cross-sectional area 1.26×10^{-3} m^2 and length 0.50 m. The difference between the temperature of the hot part of the rod and the cold part of the rod is 27°C. Give your answer to an appropriate number of significant figures.

Thermal conductivity of aluminium = 235 W K^{-1} m^{-1}

The rate of energy transfer is 1 16 ✓ J s^{-1}

Accepted answers and explanation

#1 16

16 Js-1

16Js^-1

16 J/s

16J/s

-16

-16 Js-1

-16Js^-1

-16 J/s

-16J/s

General explanation

$A = 1.26 \times 10^{-3}\ \mathrm{m}^2$

$l = 0.50\ \mathrm{m}$

$\Delta T = 27\ ^\circ\mathrm{C}$

$k = 235\ \mathrm{W\ m^{-1}\ K^{-1}}$

$$\begin{aligned}\frac{\Delta Q}{\Delta t} &= -kA\frac{\Delta T}{\Delta x} \\ &= -235 \times 1.26 \times 10^{-3} \times \frac{27}{0.50} \\ &= -15.9894 \\ &= -16\ \mathrm{J\ s^{-1}}\ (2\ \mathrm{s.f.})\end{aligned}$$

Student view

Question 5

SL HL Difficulty:

Overview
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Two metal rods, A and B, with a circular cross-sectional, have the same length and an identical rate of heat transfer $\left(\frac{\Delta Q}{\Delta t}\right)$. If rod A has twice the diameter of rod B, and twice the thermal conductivity (*k*) of rod B, what is the ratio $\frac{\Delta T_{\mathrm{A}}}{\Delta T_{\mathrm{B}}}$?

1 $\frac{1}{8}$ ✓

2 8

3 $\frac{1}{4}$

4 4

Explanation

	A	B
$\frac{\Delta Q}{\Delta t}$	$\frac{\Delta Q}{\Delta t}$	$\frac{\Delta Q}{\Delta t}$
k	$2k$	k
A	$\pi\left(\frac{2d}{2}\right)^2$	$\pi\left(\frac{d}{2}\right)^2$
ΔT	?	?
Δx	Δx	Δx

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

$$1 = kA\frac{\Delta T}{1}$$

$$\frac{1}{KA} = \Delta T$$

ΔT is inversely proportional to K

ΔT is inversely proportional to A

A is given by πr^2 so:

ΔT is inversely proportional to r^2

If K is divided by 2, ΔT is multiplied by 2, therefore ΔT_{B} will be $2\Delta T_{\mathrm{A}}$.

If *r* is divided by 2, ΔT is multiplied by 2^2, therefore ΔT_{B} will be $4\Delta T_{\mathrm{A}}$.

Student view

Overview
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Multiplying these two scale factors gives:

$$
\begin{aligned}
2\times 4 &= 8 \\
\Delta T_B &= \Delta T_A \\
\frac{\Delta T_A}{\Delta T_B} &= \frac{1}{8}
\end{aligned}
$$

Question 6

SL HL Difficulty:

The end of an aluminium rod of cross-sectional area 0.035 m^2 and length 2.0 m is heated in a flame. The end of the rod that is in the flame reaches thermal equilibrium with the flame. It is then heated for a further 3 minutes, during which time 300 000 J of energy is supplied. At the end of the 3 minutes, the cold end of the rod has a temperature of 22 °C. Calculate the temperature of the flame. Give your answer to an appropriate number of significant figures and without a unit.

Thermal conductivity of aluminium = 235 W K^{-1} m^{-1}

The temperature of the flame is 1 430 ✓ °C.

Accepted answers and explanation

#1 430

General explanation

$A = 0.035\ \mathrm{m}^2$

$\Delta x = 2.0\ \mathrm{m}$

$t = 3\ \text{minutes} = 3\times 60 = 180\ \mathrm{s}$

$\Delta Q = 300\,000\ \mathrm{J}$

$T_1 = 22\ ^\circ\mathrm{C}$

$k = 235\ \mathrm{W\ m^{-1}\ K^{-1}}$

$$
\begin{aligned}
\frac{\Delta Q}{\Delta t} &= kA\frac{\Delta T}{\Delta x} \\
\Delta T &= \frac{\Delta Q\Delta x}{\Delta t k A} \\
T_2 - T_1 &= \frac{\Delta Q\Delta x}{\Delta t k A} \\
T_2 &= \frac{\Delta Q\Delta x}{\Delta t k A} + T_1 \\
&= \frac{300\,000\times 2.0}{180\times 235\times 0.035} + 22 \\
&= 427.27 \\
&= 430\ ^\circ\mathrm{C}\ (2\ \text{s.f.})
\end{aligned}
$$

Solution Steps	Calculations
Step 1: write out the values given in the question	$A = 0.035\ \mathrm{m}^2 \Delta x = 2.0\ \mathrm{m} t = 3\ \text{minutes} \Delta Q = 300\,000\ \mathrm{J} T_1 = 22\ ^\circ\mathrm{C} k = 235\ \mathrm{W\ m^{-1}\ K^{-1}}$

Student view

Overview
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Solution Steps	Calculations
Step 2: convert the values to the units required for the equation	$t = 3\times 60t = 180\text{ s}$
Step 3: write out the equation	$\frac{\Delta Q}{\Delta t} = kA\frac{\Delta T}{\Delta x}$
Step 4: rearrange the equation to make T2 the subject	$\Delta T = \frac{\Delta Q \Delta x}{\Delta t k A}$ $T_2 - T_1 = \frac{\Delta Q \Delta x}{\Delta t k A}$ $T_2 = \frac{\Delta Q \Delta x}{\Delta t k A} + T_1$
Step 5: substitute the values given	$\frac{300\,000 \times 2.0}{180 \times 235 \times 0.035} + 22$
Step 6: state the answer to an appropriate number of significant figures with appropriate units	$T_2 = 427.27\,^{\circ}\text{C}$ The appropriate number of significant figures is 2 as this is the smallest number of significant figures in the question. $T_2 = 430\,^{\circ}\text{C}$

B. The particulate nature of matter / B.1 Thermal energy transfers

Black body emission

B.1.14: Quantitative analysis of energy transferred by radiation B.1.15: The concept of apparent brightness B.1.16: Luminosity of a body B.1.17: The emission spectrum of a black body

Learning outcomes

By the end of this section you should be able to:

- Describe what a black body is and apply Wien's law to calculate its temperature based on the peak wavelength emitted.
- Calculate the luminosity of black bodies and apply the Stefan-Boltzmann law to compare the power emitted by them.

Student view

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Figure 1. Stars in a dark sky.

Credit: David Clapp, Getty Images

Have you ever gazed up at the night sky to see millions of stars twinkling back at you (**Figure 1**)? These stars are trillions of kilometres away – some of them much, much further. They are so far away that their light might have taken thousands of years to arrive on Earth. And yet, we can study them in detail – scientists know their size, temperature, and even the materials they are made from. How can we study something so accurately when it is so far away?

Intensity

Stars emit thermal radiation equally in all directions. The greater the distance from a star, the more spread out the energy. Intensity is the amount of power incident on one square metre of the surface of an object. As the distance from a star increases, the energy is more spread out and therefore its intensity decreases.

Making connections

Power is the rate of energy transfer, calculated using the equation $P = \frac{\Delta W}{\Delta t}$ (see section A.3.3 (/study/app/math-aa-hl/sid-423-cid-762593/book/power-and-efficiency-id-43086/)).

This equation can be used to calculate the rate at which a star transfers energy.

You can calculate the intensity of a star's energy at a distance, r, from the star, by dividing the power of the star by the area over which the energy is spread (see **Table 1**).

Student
view

Table 1. Equation for intensity.

Equation	Symbols	Units
$I = \frac{P}{A}$	I = intensity	watts per metre squared (W m^{-2})
	P = power	watts (W)
	A = area	metres squared (m^2)

Because the distance from a star to an observer is usually much, much greater than the diameter of the star, for these calculations, we can treat a star as a point source, i.e. one with negligible volume. Imagine that the star is inside a larger sphere, and that the energy from the star is incident on the inside surface of the sphere (**Figure 2**). No matter the size of the sphere, its surface will receive the same total energy from the star, but the larger the radius of the sphere, the less intense the energy.

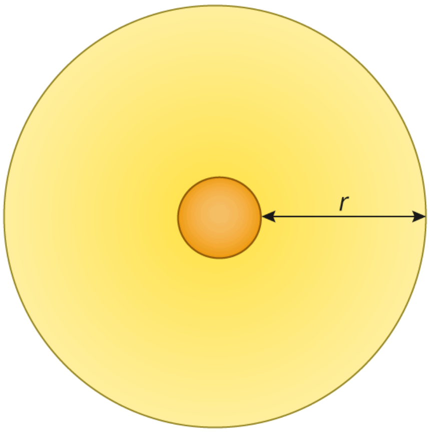

Figure 2. A star within a sphere; the star emits energy that gets less intense the further away from the star.

More information for figure 2

The image shows a diagram illustrating a star and its energy distribution within a larger spherical surface. At the center, there is a small orange circle representing the star, marked with an arrow pointing from the star's surface to the larger yellow sphere's inner surface, labeled with 'r' to indicate the radius. This radius signifies the distance between the star and any point on the sphere where the energy is less intense. The diagram visually represents the concept that as the radius increases, the energy becomes less intense, due to being spread over a larger area.

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Overview
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As the energy from a star is distributed over a spherical surface, the area in the equation $I = \frac{P}{A}$ is the area of this sphere, with radius r. The equation then becomes:

$$I = \frac{P}{4\pi r^2}$$

As power, 4 and π are constants, $I \propto \frac{1}{r^2}$, or intensity is inversely proportional to the distance squared between the star and the object on which its energy is incident. This means that if the distance increases by a factor of 2, the intensity of the incident energy decreases by a factor of 2^2.

Study skills

The inverse square law

In science, there are many inverse square relationships. An inverse square relationship is one in which if one variable increases by a factor, the other variable decreases by the same factor **squared**.

Figure 3 shows how the intensity of the energy from a star reduces as the distance, r, from the star to an object increases.

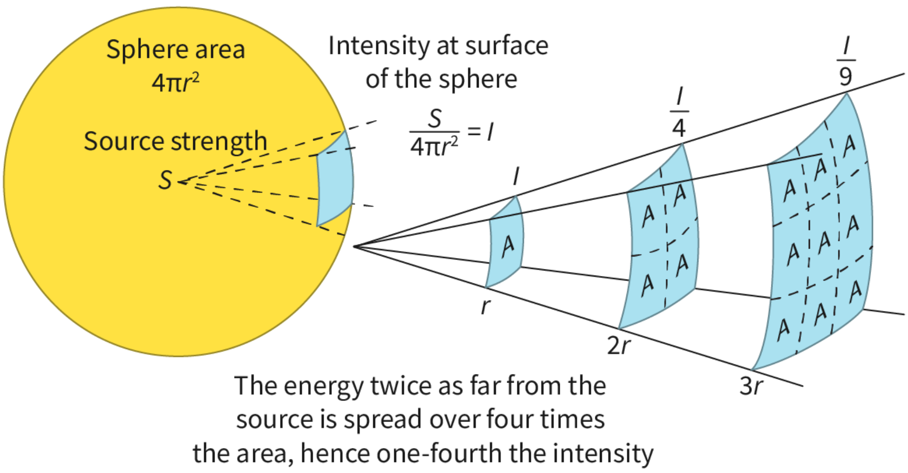

Figure 3. The inverse square law for energy intensity.

More information for figure 3

The diagram illustrates the inverse square law for energy intensity. It shows a large yellow sphere representing a light source with source strength "S" at the center. The sphere's surface area is labeled as "4πr²." From the source, lines diverge outward intersecting three blue curved surfaces labeled with distances r, 2r, and 3r from the source. At distance r, the intensity is denoted as "I." At 2r, the intensity reduces to "I/4," and at 3r, it is "I/9." The diagram includes text explaining that the energy, when measured at a distance twice as far from the source, spreads over four times the area, thus reducing its intensity to one-fourth. Similarly, at thrice the distance, it spreads over nine times the area, decreasing the intensity to one-ninth.

Student view

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Overview (/study/app/math-aa-hl/sid-423-cid-762593/c

Worked example 1

Calculate the intensity of the Sun at the Earth's surface.

The Sun is 1.5×10^{11} m away from the Earth and has a power of 4.0×10^{26} W.

Solution steps	Calculations
Step 1: write out the values given in the question and convert the values to the units required for the equation	$P = 4.0\times10^{26}\ \mathrm{W} r = 1.5\times10^{11}\ \mathrm{m}$
Step 2: calculate the area over which the Sun's energy is distributed	$A = 4\pi r^2$ $= 4\pi\left(1.5 \times 10^{11}\right)^2$ $= 2.827\times10^{23}\ \mathrm{m}^2$
Step 3: write out the equation	$I = \frac{P}{A}$
Step 4: substitute the values given	$= \frac{4.0 \times 10^{26}}{2.827 \times 10^{23}}$
Step 5: state the answer with appropriate units and the number of significant figures used in rounding	$= 1414 = 1400\ \mathrm{W\ m^{-2}}\ (2\ \mathrm{s.f.})$

Watch the video to see the method Professor Brian Cox uses to find the power incident on the Earth's surface. Critically analyse the method to find reasons for the difference between the value you calculated, and the value measured in the video? Can you suggest or research an improved method?

Student view

Overview (/study/app/math-aa-hl/sid-423-cid-762593/c

Video 1. The Sun's energy at the Earth's surface.

Black bodies

In order to study stars, scientists make assumptions about them, for example, that they are perfect spheres. Another assumption is that stars emit all wavelengths of light from the electromagnetic spectrum. That is, that they are black bodies.

A black body is an object that absorbs all the energy of all the wavelengths of the electromagnetic spectrum that fall incident upon it. Once the object is in equilibrium, it will emit all wavelengths of the electromagnetic spectrum. As the best emitters are also the best absorbers of radiation a black body can be described as an object that absorbs and emits all wavelengths of the electromagnetic spectrum.

Black bodies are ideal, meaning that no real object is a perfect black body, but there are some objects, such as stars, which are very good approximations to black bodies.

Theory of Knowledge

Nothing is a true black body, but it is very helpful for physicists to approximate things to be black bodies. To what extent does this approximation help or hinder the true understanding of scientific phenomena?

Black body emission spectrum

Figure 4 shows the emission spectrum for a black body at 6000 K.

Student view

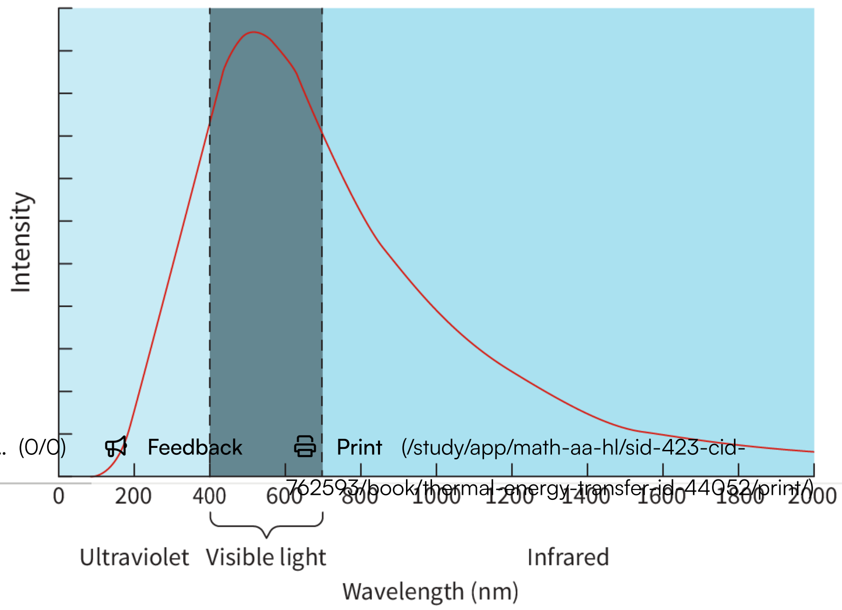

Figure 4. The emission spectrum for a black body at 6000 K.

More information for figure 4

The graph illustrates the emission spectrum of a black body at 6000 K. The X-axis represents the wavelength in nanometers (nm), ranging from 0 to 2000 nm. Key sections include the ultraviolet range (0 to 400 nm), visible light (400 to 700 nm), and infrared range (beyond 700 nm). The Y-axis represents intensity. A red curve shows the intensity distribution, peaking around the visible light region. The curve rises in the ultraviolet region, peaks near 500 nm, and then gradually decreases through the infrared region. The shaded area emphasizes the visible light region. There are no numerical intensity values on the Y-axis, but the trend is clearly represented by the curve form.

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The graph has the following features:

- It shows that some radiation is emitted at all wavelengths.
- It has a maximum intensity at a specific wavelength.
- It is not symmetrical – it rises steeply then drops off less steeply after the peak and approaches the x-axis as an asymptote.
- It does not pass through the origin.

Figure 5 shows emission spectra for black bodies at different temperatures.

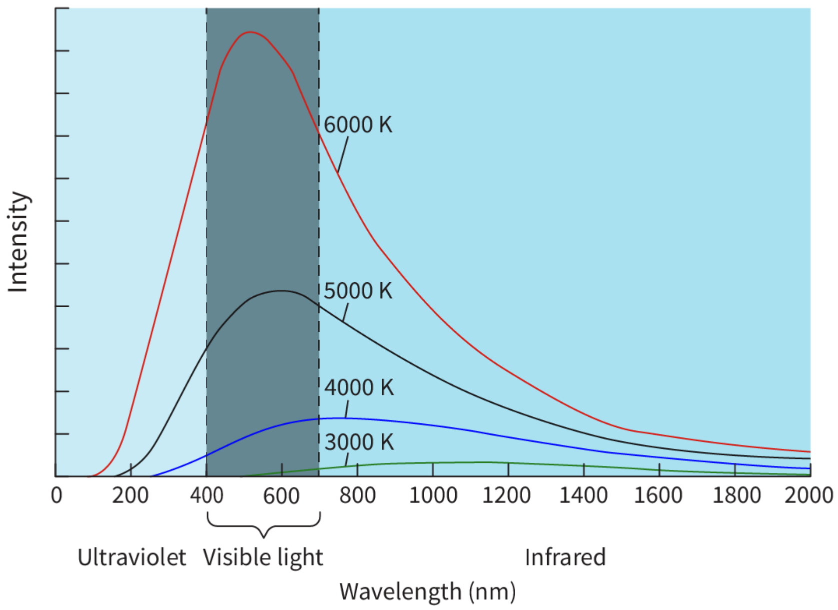

Figure 5. Emission spectra for black bodies at different temperatures.

More information for figure 5

The image is a graph showing the emission spectra for black bodies at different temperatures. The X-axis represents wavelength in nanometers, ranging from 0 to 2000 nm. It is labeled with segments for ultraviolet, visible light, and infrared. The Y-axis represents intensity, with labels but no specific numeric values indicated.

There are four curves on the graph, each representing a different temperature: 3000 K, 4000 K, 5000 K, and 6000 K. As the temperature increases, the peak of the emission curve shifts to shorter wavelengths and higher intensities.

- The curve for 3000 K peaks in the infrared region with a relatively low intensity.
- The 4000 K curve also peaks in the infrared, with higher intensity than the 3000 K curve.
- The curve for 5000 K peaks in the visible light range but extends into both the ultraviolet and infrared regions, showing a further increase in peak intensity.
- The 6000 K curve peaks in the visible light section and illustrates the highest intensity of all the curves, continuing far into the infrared region.

Overall, the graph illustrates that higher temperature black bodies emit more intensity and peak at shorter wavelengths.

[Generated by AI]

How is the curve different for a black body with a lower temperature?

Student view

Use **Interactive 1** to check your understanding of the relationship between the emission spectra of a black body and its temperature.

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Interactive 1. Black Body Radiation and Temperature: Key Terms

The shape of these graphs and the peak wavelength are not dependent on the material. The only thing that affects the peak wavelength is the temperature of the black body. This peak value can be used to determine the temperature of any black body.

In everyday life, we often use the idea of colour to describe how hot something is. Picture a piece of metal being heated in a flame (**Figure 6**). As it gets hotter, it starts to glow red, which is where the term red hot comes from. Its temperature increases and its colour turns to orange, yellow and then bright white. If something is very hot, we might even say that it is white hot.

Figure 6. Metal after being heated.

Credit: fmajor, Getty Images

Student
view

Overview
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Study skills

When water is heated on a stove in a kettle or pan, the kettle or pan does not start to visibly glow when the water is boiling. Use the graph in **Figure 5** to explain why. Discuss your ideas with your classmates, then click the button to reveal the answer.

The wavelengths emitted at the boiling temperature (approximately 373 K) are nearly all in the infrared range, and not in the visible range. The emitted infrared is invisible to humans so you do not see it.

Wien's law

Wien's law states that the wavelength at which the maximum intensity of radiation is emitted is related to the absolute temperature of a black body by the equation:

Table 2. Equation for Wien's law.

Equation	Symbols	Units
$\lambda_{\max} T = 2.9 \times 10^{-3}\,\mathrm{m\,K}$	$\lambda_{\max}$ = wavelength at which maximum intensity is emitted	metre (m)
	T = absolute temperature	kelvin (K)

Study skills

When writing metres kelvin, it is important to write it as m K, leaving a space between the m and the K. This is because mK, without a space between the two letters, implies a unit of millikelvin, in other words, 1 × 10^{-3} kelvin.

Exercise 1

Click a question to answer

The Earth receives a lot of visible light from the Sun. This is shown by the calculated wavelength of maximum intensity in the exercise question, which corresponds with the visible part of the electromagnetic spectrum.

Student view

Overview (/study/app/math-aa-hl/sid-423-cid-762593/c

Luminosity and the Stefan-Boltzmann law

The luminosity of a black body, such as a star, is the amount of energy it emits per second, measured in watts (W).

Making connections

Have you noticed that the unit of luminosity and its definition are the same as the unit and definition for power?

Another way to express the luminosity of a star is by comparing it to the luminosity of the Sun, $L_\odot$. For example, the luminosity of the star Betelgeuse is about 150 000 times greater than that of our Sun, which is written as 150 000 $L_\odot$.

The luminosity of a star can be calculated using the Stefan-Boltzmann law in **Table 3**.

Table 3. Stefan-Boltzmann law.

Equation	Symbols	Units
$L = \sigma A T^4$	L = luminosity	watt (W)
	σ = Stefan-Boltzmann constant	5.67×10^{-8} W m^{-2} K^{-4}
	A = surface area of the sphere	metres squared (m^2)
	T = absolute temperature	kelvin (K)

As σ is a constant, the Stefan-Boltzmann law tells us that the luminosity is directly proportional to the area of a star and also directly proportional to its absolute temperature, raised to the power 4.

Study skills

Remember that the shape of a star can be approximated to a sphere, whose surface area is calculated using the equation in **Table 4**.

Table 4. Equation for surface area.

Equation	Symbols	Units
$A = 4\pi r^2$	A = surface area of sphere	metres squared (m^2)
	r = radius of sphere	metre (m)

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Note: This equation is not given in the DP physics data booklet.

We can substitute the equation for area into the equation for luminosity to get:

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

As $4\pi\sigma$ is a constant, we can also say that the luminosity of a star is directly proportional to its radius squared.

Worked example 2

Proxima Centauri is a star with a temperature of 3.0×10^3 K and a diameter of 214 550 km. Calculate its luminosity.

Solution steps	Calculations
Step 1: write out the values given in the question and convert the values to the units required for the equation	$T = 3.0 \times 10^3 \text{ K} d = 214\,550 \text{ km} \quad = 214\,550 \times 10^3 \text{ m}$
Step 2: calculate the radius of the sphere	$r = \frac{d}{2}$ $= \frac{214\,550 \times 10^3}{2}$ $= 1.07275 \times 10^8 \text{ m}$
Step 3: calculate the area of the sphere	$A = 4\pi r^2$ $= 4\pi\left(1.07275 \times 10^8\right)^2$ $= 1.446 \times 10^{17} \text{ m}^2$
Step 4: write out the equation	$L = \sigma A T^4$
Step 5: substitute the values given	$= \sigma A T^4 = (5.67 \times 10^{-8}) \times (1.446 \times 10^{17}) \times (3.0 \times 10^3)^4$
Step 6: state the answer with appropriate units and the number of significant figures used in rounding	$= 6.6416 \times 10^{23} = 6.6 \times 10^{23} \text{ W (2 s.f.)}$

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Just by looking at the light from a star, its temperature can be calculated. However, if we want to know how big it is, its luminosity must be measured. This can be done by measuring how bright the star appears from Earth.

Apparent brightness

If two stars are the same distance away from an observer on Earth, the star with the greater luminosity will appear brighter to the observer. This leads us to a concept known as apparent brightness, which is how bright a star appears to an observer.

It can also be defined as the amount of power per square metre **received by an observer** from the star, measured in watts per metre squared ($W\ m^{-2}$). Apparent brightness depends on the luminosity of the star and the distance between the star and the observer.

The key difference between luminosity and apparent brightness is that luminosity is a property of the star's power output, whereas apparent brightness depends on the intensity of light received by an observer.

Study skills

The definition of apparent brightness is very similar to that of intensity. Luminosity is a property of the star's power output; apparent brightness depends on the intensity of light received by an observer.

The apparent brightness of an object can be calculated using the equation in **Table 5**.

Table 5. Equation for apparent brightness.

Equation	Symbols	Units
$b = \frac{L}{4\pi d^2}$	b = apparent brightness	watts per metre squared ($W\ m^{-2}$)
	L = luminosity	watt (W)
	d = distance between the emitter and the observer	metres (m)

This equation tells us that the brightness of a star is directly proportional to its luminosity and inversely proportional to the square of its distance from the observer.

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Making connections

Inverse square laws are common in physics (see topic D (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-44096/)).

Worked example 3

The brightest star visible in the night sky is Sirius, whose luminosity is approximately 1.0×10^{26} W.

Calculate the apparent brightness of Sirius, if the distance from Sirius to Earth is 8.1×10^{16} m.

Solution steps	Calculations
Step 1: write out the values given in the question	$L = 1.0 \times 10^{26}\ \mathrm{W} d = 8.1 \times 10^{16}\ \mathrm{m}$
Step 2: write out the equation	$b = \frac{L}{4\pi d^2}$
Step 3: substitute the values given	$= \frac{1.0 \times 10^{26}}{4\pi \times \left(8.1 \times 10^{16}\right)^2}$
Step 4: state the answer to an appropriate number of significant figures with appropriate units	$= 1.213 \times 10^{-9} = 1.2 \times 10^{-9}\ \mathrm{W\ m^{-2}}\ (2\ \mathrm{s.f.})$

Assessment questions may require you to combine several different equations, as demonstrated in the following worked example.

Worked example 4

A star of diameter 110×10^6 km emits energy with a peak wavelength of 240 nm and apparent brightness of 5.5×10^{-14} W m^{-2}.

Calculate how far the star is from the Earth.

Stage 1. Apply Wien’s law to calculate the temperature of the star.

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Solution steps	Calculations
Step 1: write out the values given in the question and convert the values to the units required in the question	$\lambda_{\text{max}} = 240 \text{ nm} = 240 \times 10^{-9} \text{ m}$
Step 2: write out the equation	$\lambda_{\text{max}} T = 2.9 \times 10^{-3} \text{ m K}$
Step 3: rearrange the equation to make T the subject	$T = \frac{2.9 \times 10^{-3}}{\lambda_{\text{max}}}$
Step 4: substitute the values given	$= \frac{2.9 \times 10^{-3}}{240 \times 10^{-9}}$
Step 5: state the answer to an appropriate number of significant figures with appropriate units	$T = 12\,083 \text{ K}$

Stage 2. Apply the luminosity equation to calculate the luminosity of the star.

Solution steps	Calculations
Step 1: write out the known values and convert the values to the units required for the equation	$T = 12\,083 \text{ K}$ $d = 110 \times 10^{6} \text{ km} = 1.1 \times 10^{11} \text{ m}$
Step 2: calculate the radius of the sphere	$r = \frac{d}{2} = \frac{1.1 \times 10^{11}}{2} = 5.5 \times 10^{10} \text{ m}$
Step 3: calculate the area of the sphere	$A = 4\pi r^2$ $A = 4\pi \left(5.5 \times 10^{10}\right)^2 = 3.801 \times 10^{22} \text{ m}^2$
Step 4: write out the equation	$L = \sigma A T^4$
Step 5: substitute the values given	$= \sigma A T^4 = 5.67 \times 10^{-8} \times 3.80 \times 10^{22} \times 12\,083^4$
Step 6: state the answer to an appropriate number of significant figures with appropriate units	$= 4.59 \times 10^{31} \text{ W}$

Stage 3. Rearrange and apply the apparent brightness equation to calculate the distance of the star from Earth.

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Solution steps	Calculations
Step 1: write out the known values	$L = 4.59 \times 10^{31}$ W$b = 5.5 \times 10^{-14}$ W m^{-2}
Step 2: write out the equation	$b = \frac{L}{4\pi d^2}$
Step 3: rearrange the equation to make d the subject	$d = \sqrt{\frac{L}{4\pi b}}$
Step 4: substitute the values given	$= \sqrt{\frac{4.59 \times 10^{31}}{4\pi \times 5.5 \times 10^{-14}}}$
Step 5: state the answer to an appropriate number of significant figures with appropriate units	$= 8.149 \times 10^{21} = 8.1 \times 10^{21}$ m (2 s.f.)

Try the following activity to check your understanding of black body emissions.

Activity

- **IB learner profile attribute:** Knowledgeable
- **Approaches to learning:** Thinking skills — Reflecting at all stages of the assessment and learning cycle
- **Time required to complete activity:** 30 minutes
- **Activity type:** Individual activity

Research the apparent brightness of the following stars and their distance from the Earth. Create a suitable table to record your data.

Canopus	Rigel Kentaurus	Arcturus
Vega	Capella	Rigel
Procyon	Achernar	Betelgeuse

Plot a graph with the Earth-star distance on the *x*-axis and the apparent brightness on the *y*-axis. What relationship do you observe? What could you plot on the *x*- and *y*-axes in order to linearise this graph?

Student view

What relationship does the apparent brightness equation show between apparent

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brightness and distance?

6 section questions

Question 1

SL HL Difficulty:

Black bodies are objects that emit radiation at 1 all ✓ wavelengths of the electromagnetic spectrum.

Accepted answers and explanation

#1 all

every

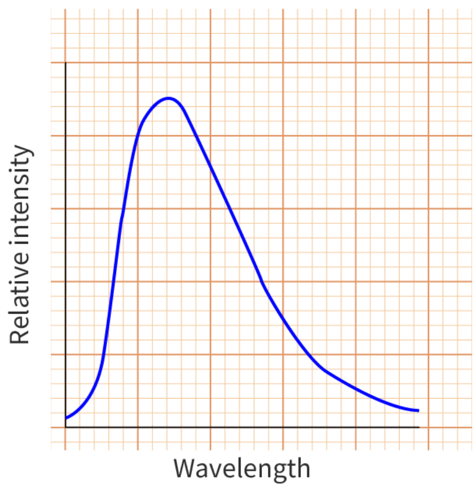
General explanation

Black bodies are objects that emit radiation at all wavelengths of the electromagnetic spectrum.

Question 2

SL HL Difficulty:

The graph shows the emission spectrum for a black body at a temperature, *T*. Another line is to be plotted for a black body with a **higher** temperature. State in which direction you would expect the location of the peak of the curve to move.



More information

1 Up and left ✓

2 Up and right

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3 Down and left

4 Down and right

Explanation

A black body at a higher temperature emits maximum intensity of radiation at a lower wavelength.

Question 3

SL HL Difficulty:

Procyon is a star with a temperature of 7740 K and an area of 2.4×10^{13} m^2. Calculate its luminosity.

1 4.9×10^{21} W ✓

2 1.1×10^{10} W

3 8.6×10^{28} W

4 8.2×10^{13} W

Explanation

$T = 7740\ \mathrm{K}$

$A = 2.4{\times}10^{13}\ \mathrm{m}^2$

$$\begin{aligned} L &= \sigma A T^4 \\ &= 5.67 \times 10^{-8} \times 2.4 \times 10^{13} \times 7740^4 \\ &= 4.884{\times}10^{21} \\ &= 4.9{\times}10^{21}\ \mathrm{W}\ (2\ \mathrm{s.f.}) \end{aligned}$$

Question 4

SL HL Difficulty:

Star A has a luminosity *L* and, when observed from a distance, *d*, away, its apparent brightness is *b*. Star B has luminosity 2*L* and is twice as far away as Star A.

What is its apparent brightness?

1 $\frac{b}{2}$ ✓

2 b

3 $4b$

4 $8b$

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Explanation

The equation for apparent brightness is:

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

Apparent brightness is directly proportional to luminosity. Therefore, if luminosity increases by a factor of 2, apparent brightness also increases by a factor of 2. Therefore brightness becomes 2*L*.

Apparent brightness is inversely proportional to distance. Therefore if distance increases by a factor of 2, luminosity decreases by a factor of 2^2, which is 4.

These two relationships can be combined to give:

$$\begin{aligned} b_{\mathrm{B}} &= \frac{2b}{4} \\ &= \frac{b}{2} \end{aligned}$$

Question 5

SL HL Difficulty:

A star of diameter 100 × 10^6 km emits energy with a peak wavelength of 395 nm and apparent brightness of 4.8 × 10^{-14} W m^{-2}.

Calculate how far the star is from the Earth.

1 2.93 × 10^{21} m ✓

2 2.93 × 10^{15} m

3 5.18 × 10^{24} m

4 5.18 × 10^{18} m

Explanation

Stage 1. Apply Wien's law to calculate the temperature:

$$\begin{aligned} \lambda_{\max} &= 395\ \mathrm{nm} \\ &= 395 \times 10^{-9}\ \mathrm{m} \end{aligned}$$

$$\begin{aligned} \lambda_{\max} T &= 2.9 \times 10^{-3}\ \mathrm{m\ \ K} \\ T &= \frac{2.9 \times 10^{-3}}{\lambda_{\max}} \\ &= \frac{2.9 \times 10^{-3}}{395 \times 10^{-9}} \\ &= 7342\ \mathrm{K} \end{aligned}$$

Student view

Stage 2. Apply the luminosity equation to calculate the luminosity of the star:

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$$T = 7342 \text{ K}$$

$$\begin{aligned} d &= 100\times10^{6} \text{ km} \\ &= 1\times10^{11} \text{ m} \end{aligned}$$

$$\begin{aligned} r &= \frac{d}{2} \\ &= \frac{1\times10^{11}}{2} \\ &= 5.0\times10^{10} \text{ m} \end{aligned}$$

$$\begin{aligned} A &= 4\pi r^2 \\ &= 4\pi\left(5.0\times10^{10}\right)^2 \\ &= 3.142\times10^{22} \text{ m}^2 \end{aligned}$$

$$\begin{aligned} L &= \sigma A T^4 \\ &= 5.67\times10^{-8}\times3.142\times10^{22}\times7342^4 \\ &= 5.18\times10^{30} \text{ W} \end{aligned}$$

Stage 3. Rearrange and apply the apparent brightness equation to calculate the distance of the star from the Earth:

$$L = 5.18\times10^{30} \text{ W}$$

$$b = 4.8\times10^{-14} \text{ W m}^{-2}$$

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

$$\begin{aligned} d &= \sqrt{\frac{L}{4\pi b}} \\ &= \sqrt{\frac{5.18\times10^{30}}{4\pi\times4.8\times10^{-14}}} \\ &= 2.93\times10^{21} \\ &= 2.9\times10^{21} \text{ m (2 s.f.)} \end{aligned}$$

Question 6

SL HL Difficulty:

Two stars, A and B, are discovered very close to one another in space. If the luminosity of star A is twice that of star B and its temperature is also twice as great, what is the ratio $\frac{r_A}{r_B}$?

1 $\frac{\sqrt{2}}{4}$ ✓

2 $\frac{4}{\sqrt{2}}$

3 8

4 $\frac{1}{8}$

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Explanation

	A	B
L	$2L$	L
T	$2T$	T

$L = \sigma A T^4$

Substitute $A = 4\pi r^2$ into the equation:

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

Cancel out constants:

$$L \, \alpha \, r^2 T^4$$

$$r \, \alpha \sqrt{\frac{L}{T^4}}$$

$$r \, \alpha \, \frac{\sqrt{L}}{T^2}$$

Using the information given that $T_{\mathrm{A}} = 2T_{\mathrm{B}}$ and $L_{\mathrm{A}} = 2L_{\mathrm{B}}$, substituting into the equation above gives:

$$r_{\mathrm{A}} \, \alpha \, \frac{\sqrt{L_{\mathrm{A}}}}{{T_{\mathrm{A}}}^2}$$

$$r_{\mathrm{A}} = \frac{\sqrt{2L_{\mathrm{B}}}}{2^2{T_{\mathrm{B}}}^2} = \frac{2}{\sqrt{4}} r_{\mathrm{B}}$$

$$\frac{r_{\mathrm{A}}}{r_{\mathrm{B}}} = \frac{\sqrt{2}}{4}$$

B. The particulate nature of matter / B.1 Thermal energy transfers

Summary and key terms

Section Student… (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/summary-and-key-terms-id-44053/print/) Assign

- Matter is anything that is made of particles with mass. Depending on the arrangement of the particles, how much energy they have and the strength of the intermolecular forces between them, they can be classified as either solids, liquids or gases.
- Internal energy is the total intermolecular potential energy plus the total random kinetic energy of the particles arising from their random motion.

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- The density of a substance is a measure of how much mass it has per unit volume, measured in kilograms per cubic metre, kg m^{-3}. Solids have the highest density, while gases have the lowest.
- While we use either the degrees Fahrenheit, °F, or degrees Celsius, °C, to describe temperature in everyday life, scientists often use the absolute temperature or Kelvin scale. At absolute zero, or 0 kelvin, molecules of an ideal gas have theoretically zero energy, zero pressure and zero volume. We can convert from degrees Celsius to kelvin by adding 273. A temperature change of 1 °C is the same as a temperature change of 1 K.
- The absolute temperature (temperature in kelvin) of a substance is a measure of the average kinetic energy of its molecules.
- Specific heat capacity is the amount of energy required to increase the temperature of 1 kg of a substance by 1 K, measured in joules per kilogram kelvin, J kg^{-1} K.
- When an object is heated, the thermal energy supplied is transformed to kinetic energy of the particles as well as being used to weaken the intermolecular forces, allowing particles to move further away from each other, thus increasing their potential energy.
- A change of phase occurs when a substance changes from one state (solid, liquid or gas) to another. This change of phase happens at a constant temperature because all of the energy supplied to the substance is used to increase the potential energy between particles.
- Specific latent heat is the amount of energy required to change the phase of 1 kg of a substance at constant temperature.
- Conduction is the transfer of thermal energy due to collisions between particles. For this reason, it happens best in solids. Metals are the best conductors of thermal energy because they have free electrons which can move through the metal, transferring thermal energy.
- The rate of thermal energy transferred by conduction depends on the thermal conductivity of the material, its cross-sectional area and length, and the difference in temperature between the hotter and colder parts of the material.
- Convection is the transfer of thermal energy due to the mass movement of particles and therefore happens best in liquids and gases.
- Thermal radiation is the transfer of energy by electromagnetic waves. All objects with a temperature above 0 K emit infrared radiation. Black, matt surfaces are the best emitters and absorbers of infrared radiation, while light coloured, shiny surfaces are the best reflectors.
- A black body is a theoretical object that absorbs all energy from all wavelengths of light from the electromagnetic spectrum. A black body in thermal equilibrium emits black body radiation containing *all* wavelengths of light from the electromagnetic spectrum. They do not exist in real life, but some objects, such as stars, are very close approximations to black bodies. Graphs called emission spectra illustrate the intensities of radiation that are emitted by black bodies at different wavelengths and Wien's Law tells us that the absolute temperature of the star is inversely proportional to the wavelength at which the maximum intensity of radiation is emitted.
- The luminosity of a black body is the amount of energy it emits per second, measured in watts, W. It is directly proportional to the surface area of the star and also to the absolute temperature of the star raised to the fourth power, T^4.
- The apparent brightness of a star is how bright it appears to an observer, or the amount of power per square metre *received by an observer* from the star, measured in watts per metre square, W m^{-}

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[2]. It is directly proportional to the star's luminosity and inversely proportional to the square of the distance between the star and the observer.

Key terms

Review these key terms. Do you know them all? Fill in as many ga using the terms in this list.

1. The particles in a ______ are in a regular arrangeme forces of attraction between them.
2. The best conductors are ______ because they have which carry thermal energy through the object.
3. ______ only occurs in liquids and gases because the to move.
4. The more mass there is in 1 cubic metre of a substance, the greater its ______ .
5. ______ is the ______ temperature a have zero kinetic energy.
6. When a substance changes phase, its temperature remains
7. A ______ absorbs radiation from all parts of the elect spectrum.
8. The apparent brightness of a black body is ______ tc ______ to its distance from the observer.

constant | solid | metals | Absolute zero | directly proportiona | Convection | inversely proportional | black body | density

Check

Interactive 1. Thermal Physics: Key Terms Review

B. The particulate nature of matter / B.1 Thermal energy transfers

Student view

Checklist

What you should know

After studying this subtopic, you should be able to:

- Explain the molecular structure of solids, liquids and gases.
- Recognise that different temperature scales are used around the world, but they fundamentally describe the same thing.
- Explain that there is a difference between the numerical values of temperature in Kelvin and Celsius, but no difference in the magnitude of the change of temperature on these scales.
- Explain that Kelvin temperature is a measure of the average kinetic energy of particles as given by

$$\bar{E}_{\mathrm{k}} = \frac{3}{2}k_{\mathrm{B}}T$$

- Use graphs and calculations to describe what happens to a substance as it is heated.
- Analyse heat transfers and phase changes using the concepts of specific heat capacity and specific latent heat.
- Apply molecular theory to describe how thermal energy is transferred by conduction, convection and radiation.
- Describe what a black body is and apply Wien's law to calculate its temperature based on the peak wavelength emitted.
- Calculate the luminosity of black bodies and apply the Stefan-Boltzmann law to compare the power emitted by them.

Practical skills

Once you have completed this subtopic, go to Practical 3: Measuring the specific latent heat of vaporisation of water (/study/app/math-aa-hl/sid-423-cid-762593/book/measuring-the-specific-latent-heat-of-vaporisation-of-water-id-46752/) in which you will measure and calculate the transfer of thermal energy.

Investigation

- **IB learner profile attribute:** Inquirer
- **Approaches to learning:**
  - Research skills – Comparing, contrasting and validating information
  - Communication skills – Presenting data appropriately
- **Time required to complete activity:** 1 hour
- **Activity type:** Individual activity

Your task

The closest solar system to our Solar System is a triple solar system called Alpha Centauri. The Alpha Centauri solar system has only three planets, all of which orbit the central star in the system, Proxima Centauri. The only one of these planets whose orbit is in the habitable zone of Alpha Centauri is called Proxima B. Some data about this solar system is provided in **Table 1.**

Table 1. Data about Alpha Centauri.

Star	Surface temperature (K)	Radius (km)	Distance to Proxima B (km)
Proxima Centauri	3000	110 000	7.3×10^{6}
Alpha Centauri A	5800	850 000	1.9×10^{12}
Alpha Centauri B	5300	600 000	1.9×10^{12}

Imagine that you are an aerospace engineer preparing for the first human settlement on the planet Proxima B. Apply your understanding from this subtopic, and use information from **Table 1**, plus your own research, to prepare a detailed report to your team about the conditions on the planet. You may wish to think about:

- the temperatures on the planet
- the phase of matter of any water that may exist on the planet
- the brightness of the planet's stars.

How might these factors affect the possibility of human life on the Proxima B?

Making connections

What applications does the Stefan-Boltzmann law have in astrophysics?

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B. The particulate nature of matter / B.1 Thermal energy transfers

Reflection

Section Student... (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/reflection-id-47872/print/) Assign

Teacher instructions

The goal of this section is to encourage students to reflect on their learning and conceptual understanding of the subject at the end of this subtopic. It asks them to go back to the guiding questions posed at the start of the subtopic and assess how confident they now are in answering them. What have they learned, and what outstanding questions do they have? Are they able to see the bigger picture and the connections between the different topics?

Students can submit their reflections to you by clicking on 'Submit'. You will then see their answers in the 'Insights' part of the Kognity platform.

Reflection

Now that you've completed this subtopic, let's come back to the guiding questions introduced in The big picture (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43777/).

- How do macroscopic observations provide a model of the microscopic properties of a substance?
- How is energy transferred within and between systems?
- How can observations of one physical quantity be used to determine the other properties of a system?

With these questions in mind, take a moment to reflect on your learning so far and type your reflections into the space provided.

You can use the following questions to guide you:

- What main points have you learned from this subtopic?
- Is anything unclear? What questions do you still have?
- How confident do you feel in answering the guiding questions?
- What connections do you see between this subtopic and other parts of the course?

⚠ Once you submit your response, you won't be able to edit it.

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Rate subtopic B.1 Thermal energy transfers

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