2 Energy in transit

25.1 °C

8.2

Thermal imaging shows the temperature of these people. Their faces and hands are red and white as these areas are producing heat and are not covered by clothing.

REMEMBER

Before beginning this chapter you should be able to:

■ describe the kinetic particle model of matter
■ explain internal energy as the energy associated with random motion of molecules
■ describe temperature with reference to the average translational kinetic energy of atoms and molecules.

KEY IDEAS

After completing this chapter you should be able to:

■ describe the process of energy transfer by conduction, convection and radiation
■ identify regions of the electromagnetic spectrum as radio, microwave, infra-red, visible, ultraviolet, x-ray and gamma waves
■ compare the total energy, across the electromagnetic spectrum, emitted by objects at different temperatures
■ describe the power radiated by objects of different temperatures using Stefan–Boltzmann Law: $P \propto T^4$
■ calculate the peak wavelength of the re-radiated electromagnetic radiation from the Earth using Wien's Law: $\lambda_{max}T$ = constant.

Transfer of energy

During heating and cooling, energy is always transferred from a region of high temperature to a region of lower temperature. There are many situations in which it is necessary to control the rate at which the energy is transferred.

- Warm-blooded animals, including humans, need to maintain their body temperature in hot and cold conditions. Cooling of the body must be reduced in cold conditions. In hot conditions, it is important that cooling takes place to avoid an increase in body temperature.
- Keeping your home warm in winter and cool in summer can be a costly exercise, both in terms of energy resources and money. Applying knowledge of how heat is transferred from one place to another can help you to find ways to reduce how much your house cools in winter and heats up in summer, thus reducing your energy bills.

- The storage of many foods in cold temperatures is necessary to keep them from spoiling. In warm climates most beverages are enjoyed more if they are cold. The transfer of heat from the warmer surroundings needs to be kept to a minimum.

There are three different processes through which energy can be transferred during heating and cooling: **conduction**, **convection** and **radiation**.

Conduction

Conduction is the transfer of heat through a substance as a result of collisions between neighbouring vibrating particles. The particles in the higher temperature region have more random kinetic energy than those in the lower temperature region. As shown in the figure at left, the more energetic particles collide with the less energetic particles, giving up some of their kinetic energy. This transfer of kinetic energy from particle to particle continues until thermal equilibrium is reached. There is no net movement of particles during the process of conduction.

Solids are better conductors of heat than liquids and gases. In solids, the particles are more tightly bound and closer together than in liquids and gases. Thus, kinetic energy can be transferred more quickly. Metals are the best conductors of heat because free electrons are able to transfer kinetic energy more readily to other electrons and atoms.

Materials that are poor conductors are called **insulators**. Materials such as polystyrene foam, wool and fibreglass batts are effective insulators because they contain pockets of still air. Air is a very poor conductor of heat. If air is free to move, however, heat can be transferred by a different method — convection.

Reducing heat transfer to and from buildings saves precious energy resources, and reduces gas and electricity bills.

Conduction is the transfer of heat through a substance as a result of collisions between neighbouring vibrating particles.

Convection is the transfer of heat in a fluid (a liquid or gas) as a result of the movement of particles within the fluid.

Radiation is heat transfer without the presence of particles.

Insulators are materials that are poor conductors of heat.

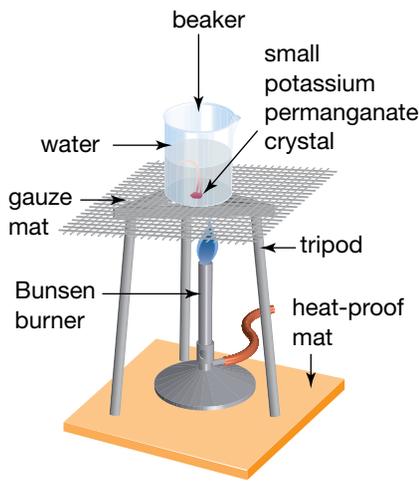direction of heat transfer

high temperature   low temperature

Conduction is the transfer of heat due to collisions between neighbouring particles.

A **convection current** is a movement of particles during the transfer of heat through a substance.

beaker
small potassium permanganate crystal
water
gauze mat
tripod
Bunsen burner
heat-proof mat

Purple particles from a crystal of potassium permanganate carefully placed at the bottom of the beaker are forced around the beaker by convection currents in the heated water.

Convection

Convection is the transfer of heat through a substance as a result of the movement of particles between regions of different temperatures. Convection takes place in liquids and gases where particles are free to move around. In solids, the particles vibrate about a fixed position and convection does not occur.

The movement of particles during convection is called a **convection current**. Faster moving particles in hot regions rise while slower moving particles in cool regions fall. The particles in the warm water near the flame in the figure on the left are moving faster and are further apart than those in the cooler water further from the flame. The cooler, denser water sinks, forcing the warm, less dense water upwards. This process continues as the warm water rises, gradually cools and eventually sinks again, replacing newly heated water.

Convection currents are apparent in ovens that do not have fans. As the air circulates, the whole oven becomes hot. However, the top part of the oven always contains the hottest, least dense air. As the air cools, it sinks and is replaced by less dense hot air for as long as the energy source at the bottom of the oven remains on. Fans can be used to push air around the oven, providing a more even temperature.

Home-heating systems use convection to move warm air around. Ducted heating vents are, where possible, located in the floor. Without the aid of powerful fans, the warm air rises, circulates around the room until it cools and sinks, being replaced with more warm air. In homes built on concrete slabs, ducted heating vents are in the ceiling. Fans are necessary to push the warm air downwards so that it can circulate more efficiently.

In summer, loose fitting clothing is more comfortable because it allows air to circulate. Thus, heat can be transferred from your body by convection as the warm air near your skin rises and escapes upwards.

Hot summer day

During hot summer days, radiant energy from the Sun heats the land and sea. The land, however, has a lower specific heat capacity than the sea, and soon has a higher temperature than the water. The air near the ground becomes hot as a result of conduction. As this air gets hot, it expands, becoming less dense than the cooler, denser air over the sea. The air over the sea rushes in towards the land, replacing the rising warm air, causing what is known as a sea breeze. Coastal areas generally experience less extreme maximum temperatures than inland areas as a result of sea breezes.

warm air rises over land
cool air replaces warm rising air
warm ground heats air
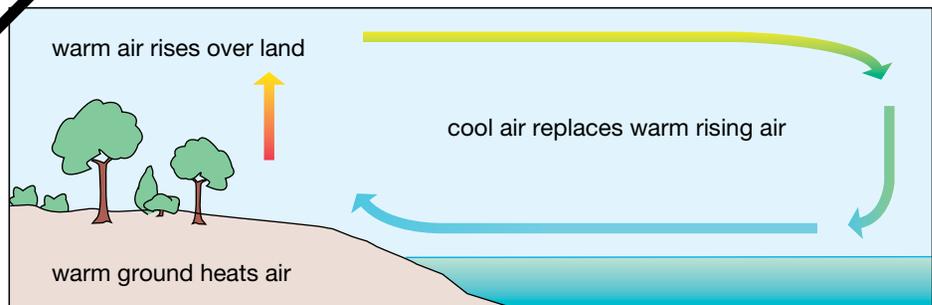
A sea breeze is caused by convection currents resulting from temperature differences between the land and the sea.

On the south coast of Australia, strong northerly winds blowing from the land will occasionally prevent convection from causing a sea breeze. When this happens in summer, temperatures can soar — often above 40 °C.

During the night, if the land becomes colder than the sea, convection currents push cool air from the land towards the sea, creating a land breeze.
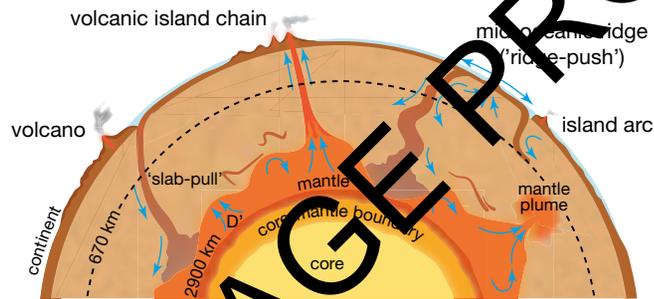
Convection inside the Earth

Energy transfer by convection is common in gases and liquids, but it can also occur in solids under the right conditions. The high temperatures, about 2000 °C, and pressures in the Earth's mantle are enough to make solid rock move, only very slowly of course. The speed of the rock movement is a few centimetres per year.

The heat energy in the Earth comes from the radioactive decay of elements such as uranium. The heat energy is not evenly distributed and hot spots occur under the mantle. The hot lighter rock at these points slowly rises, while denser rock at colder spots slowly sinks. This sets up a convection cell in the Earth's mantle with the surface crust moving horizontally across the Earth.

The molten rock wells up at mid-ocean ridges and moves out. The rock eventually meets the edge of a continental plate and cools further, becoming denser, then sinks back towards the mantle in a deep ocean trench.

New crust is formed at a ridge and returns to the mantle at a trench.

Radiation

Heat can be transferred without the presence of particles by the process of radiation. All objects with a temperature above absolute zero (0 K) emit small amounts of **electromagnetic radiation**. Visible light, microwaves, infra-red radiation, ultraviolet radiation and x-rays are all examples of electromagnetic radiation. All electromagnetic radiation is transmitted through empty space at a speed of $3.0 \times 10^8 \, \text{m s}^{-1}$, which is most commonly known as the speed of light.

Electromagnetic radiation can be absorbed by, reflected from or transmitted through substances. Scientists have used a wave model to explain much of the behaviour of electromagnetic waves. These electromagnetic waves transfer energy and reflect and refract in ways that are similar to waves on water.

What distinguishes the different types of electromagnetic radiation from each other is:

- their wavelength (the distance the wave takes to repeat itself)
- their frequency (the number of wavelengths passing every second)
- the amount of energy they transfer.

These properties in turn determine their ability to be transmitted through transparent or opaque objects, their heating effect and their effect on living tissue.

The figure below shows the electromagnetic spectrum and demonstrates that higher energy radiation corresponds to low wavelength.

The **electromagnetic spectrum** is the full range of wavelengths of all electromagnetic waves.

The electromagnetic spectrum. All objects emit some electromagnetic radiation.
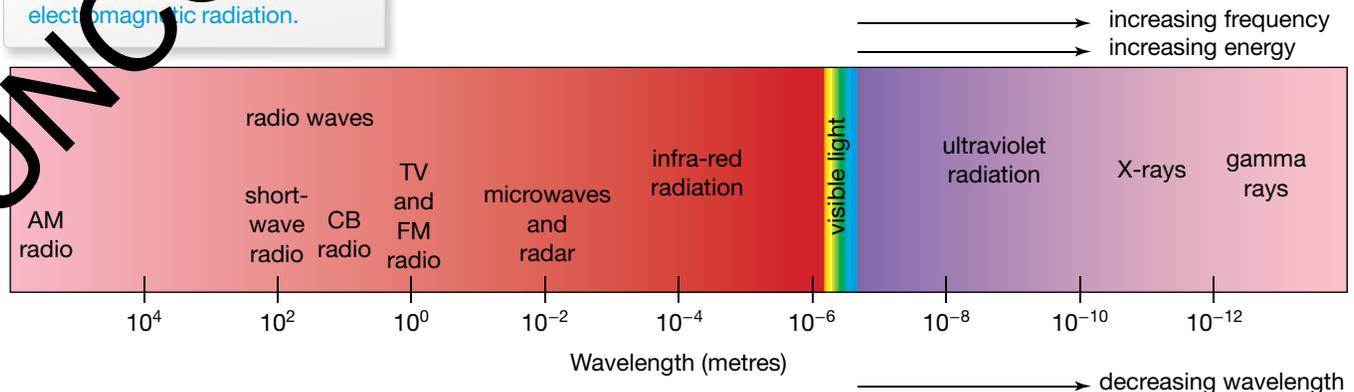
Why do hot objects emit electromagnetic radiation?

All matter is made up of atoms. At any temperature above absolute zero, these atoms are moving and colliding into each other. The atoms contain positive and negative charges. The motion of the atoms and their collisions with other atoms affect the motion of the electrons. Because they are charged and moving around, the electrons produce electromagnetic radiation. Electrons moving in an antenna produce a radio signal, but in a hot object the motion is more random with a range of speeds.
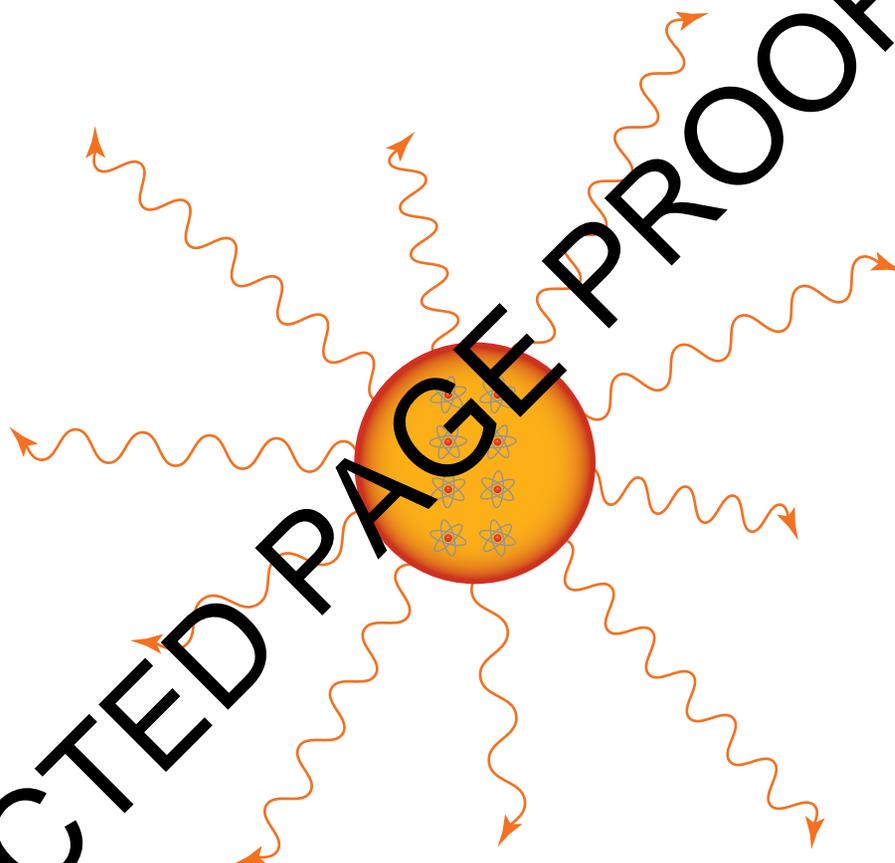
Electromagnetic radiation from a hot body

So, a hot object produces radiation across a broad range of wavelengths. If its temperature increases, the atoms move faster and have more frequent and more energetic collisions. These produce more intense radiation with higher frequencies and shorter wavelengths.

During the late 19th century, scientists conducted investigations into how much radiation was produced across the spectrum and how this distribution changed with temperature. The results are displayed in the figure on the next page.

The graphs for different temperatures are roughly the same shape. Starting from the right with long wavelengths, there is very little infra-red radiation emitted. As the wavelength gets shorter, the radiation produced increases to a maximum; finally as the wavelength shortens even further, the amount of radiation drops away quite quickly. The graphs for higher temperatures have a peak at a shorter wavelength and also have a much larger area under the graph, meaning a lot more energy is emitted.

Early researchers such as Jozef Stefan were keen to find patterns and relationships in the data and to be able to explain their observations. In 1879, Stefan compared the area under the graph for different temperatures. This area is the total energy emitted every second across all wavelengths, in other words, the power.

Intensity for different wavelengths across the electromagnetic spectrum for four different temperatures: 3000 K, 4000 K, 5000 K and 6000 K
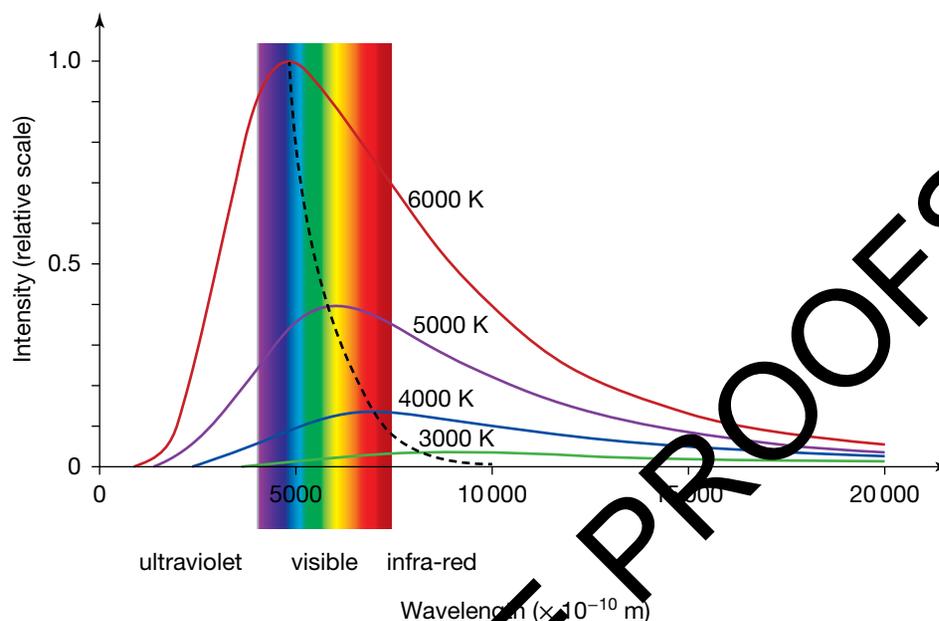
He found that the power was proportional to absolute temperature to the power of 4, that is,

power $\propto T^4$.

This means that if the absolute temperature of a hot object doubles from 1000 K to 2000 K, the amount of energy emitted every second increases by 2^4 ($2 \times 2 \times 2 \times 2 = 16$ times).

Using this relationship, Stefan was able to estimate the temperature of the surface of the Sun as 5430 °C or 5700 K, which is very close to the value known today of 5778 K.

Ludwig Boltzmann later proved this from a theoretical standpoint, and so the power $\propto T^4$ relationship is called the Stefan–Boltzmann law.

This relationship applies to all objects, but the constant of proportionality depends on the size of the object and other factors.

Sample problem 2.1

(a) When iron reaches about 480 °C it begins to glow with a red colour. How much more energy is emitted by the iron at this temperature, compared to when it is at a room temperature of 20 °C?

(b) How much hotter than 20 °C would the iron need to be to emit 10 times as much energy?

Solution: (a) **STEP 1**

Change the temperature to Kelvin.
Temperature of hot iron = 480 °C + 273 = 753 K
Temperature of cold iron = 20 °C + 273 = 293 K

STEP 2

Calculate the ratio.
Ratio of power (hot to cold) = Ratio of temperatures to the power of 4

$$\frac{P_{hot}}{P_{cold}} = \left(\frac{T_{hot}}{T_{cold}}\right)^4 = \left(\frac{753}{293}\right)^4 = 44$$

The hot iron emits 44 times as much energy every second as it does when it is at room temperature.

(b) **STEP 1**

Change the temperature to Kelvin.
Temperature of cold iron = 20 °C + 273 = 293 K

STEP 2

Calculate the ratio.
Ratio of power (hot to cold) = Ratio of temperatures to the power of 4

$$\frac{P_{\text{hot}}}{P_{\text{cold}}} = \left(\frac{T_{\text{hot}}}{T_{\text{cold}}}\right)^4$$

$$10 = \left(\frac{T_{\text{hot}}}{293}\right)^4$$

This can be rearranged to give $10^{\frac{1}{4}} = \frac{T_{\text{hot}}}{293}$.

To calculate $10^{\frac{1}{4}}$, you can use the x^y key on your calculator.

First enter the number for x, in this case 10, then push the x^y key, then enter the number for y, in this case 0.25, which is $\frac{1}{4}$ as a decimal. Then hit the equals key. You should get the answer 1.778.

$$1.778 = \frac{T_{\text{hot}}}{293}$$

$$T_{\text{hot}} = 1.778 \times 293 = 521 \text{ K}$$

**STEP 3**

Change the temperature to Celsius.
Temperature of hot iron = 521 − 273 = 248 °C

At 248 °C, the iron will emit 10 times as much energy every second as iron at 20 °C.

Revision question 2.1

The Sun has a surface temperature of 5778 K and radiates energy at a rate of 3.846×10^{26} watts. How much energy would a star of similar size radiate if its surface temperature was 8000 K?

Wilhelm Wien (pronounced *Veen*) in 1893 was able to show that as the temperature increased, the wavelength of maximum intensity of energy emitted decreased, and indeed the two quantities were inversely proportional. That is, the wavelength is proportional to the inverse of the temperature. This can be seen in the graph on the right.
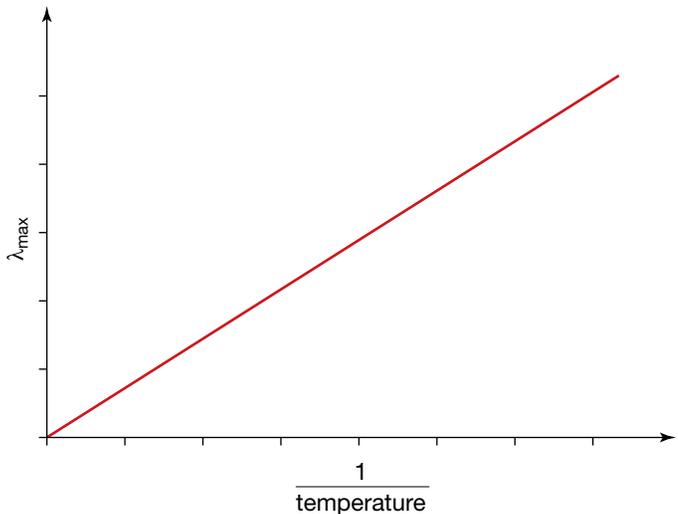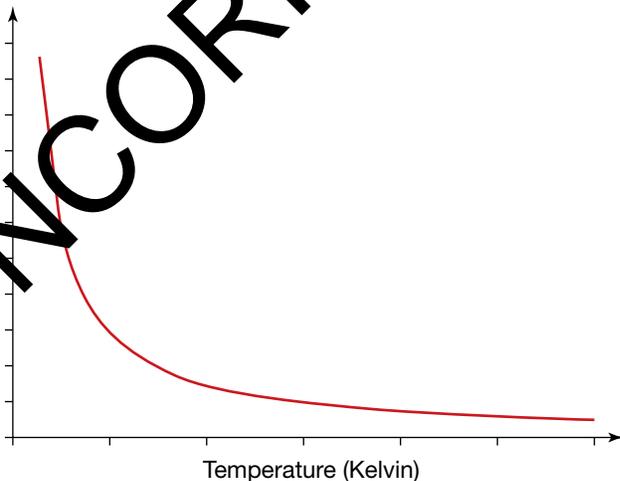
Wien's law can be written as $\lambda_{max} \times T = $ constant. The value of this constant is 2.90×10^{-3} mK (metre–degree Kelvin).

Sample problem 2.2

(a) At what wavelength is the peak intensity of the light coming from a star whose surface temperature is 11 000 K (about twice as hot as the Sun)?
(b) In what section of the spectrum is this wavelength?

Solution: (a) $\lambda_{max} = \dfrac{2.90 \times 10^{-3}\,\text{mK}}{11\,000\,\text{K}}$

$= 2.636 \times 10^{-7}\,\text{m}$

1 nanometre $= 10^{-9}$ m, so $\lambda_{max} = 263.6 \times 10^{-9}$ m $= 264$ nm

(b) 264 nm is beyond the violet end of the visible spectrum, so it is in the ultra-violet section of the electromagnetic spectrum.

Revision question 2.2

Determine the surface temperature of a star that emits light at a maximum intensity of 450 nm.

Summary

- Heat energy can be transferred by conduction, convection and radiation.
- Conduction is the transfer of heat energy through a material by collisions between adjacent particles.
- Some materials conduct heat energy well and are called conductors. Others do not and are called insulators.
- Convection is the transfer of heat energy through a substance, usually a liquid or a gas, by the movement of particles between regions of different temperature. Hotter material is less dense because faster moving particles push each other further apart. If free to move, the less dense and hotter material will rise, displacing cooler material.
- The movement of plates in the Earth's crust is caused by convection from heat energy within the Earth.
- Radiation is the transfer of heat energy by the emission of electromagnetic radiation.
- The emitted radiation comes from a range of wavelengths across the electromagnetic spectrum.
- The graph of the energy contribution of different wavelengths of emitted radiation has a characteristic shape.
- For a given temperature, there is a specific wavelength at which the most energy is emitted. Its symbol is λ_{max}.
- The graph of the energy contribution of different wavelengths for a higher temperature has a lower λ_{max} and a larger area under the graph.
- λ_{max} is inversely proportional to the temperature measured in Kelvin ($\lambda_{max}T$ is constant).
- The amount of energy emitted per second is called power.
- The area under the graph of energy contribution against wavelength is a measure of power.
- The area under the graph is proportional to the Kelvin temperature raised to the power of four. This can be expressed as power $\propto T^4$.

Questions

Transfer of energy

1. Explain with the aid of a well-labelled diagram how heat is transferred through a substance by conduction.
2. Why are liquids and gases generally poorer conductors of heat than solids?
3. Explain in terms of conduction and convection why you don't heat a test tube of water with the Bunsen burner flame near the top of the test tube.

4. Explain with the aid of a well-labelled diagram how convection occurs in a liquid that is being heated from below.
5. Why is it not possible for heat to be transferred through solids by convection?
6. At what speed does radiant energy move through space? What is significant about this speed?
7. When you swim in a still body of water on a hot afternoon there is a noticeable temperature difference between the water at the surface and the deeper water.
   (a) Explain why this difference occurs.
   (b) If the water is rough, the difference is less noticeable. Why?
8. The daytime temperature of an area can decrease for several days after a major bushfire. Why does this happen?
9. The microwave cooking instructions for frozen pies state that pies should be left to stand for two minutes after heating. What happens to the pie while it stands?
10. Standing near the concrete wall of a city building after a hot day you can instantly feel its warmth from a few metres away.
    (a) How is the energy transferred to you?
    (b) What caused the building to get hot during the day?
11. Why is it not practical to drink hot coffee in an aluminium picnic cup?
12. Why do ducts in the ceiling need more powerful fans than those in the floor?
13. Why do conventional ovens without fans have heating elements at the bottom. What is the advantage of having an oven with a fan?

Stefan–Boltzmann Law

14. A 100 W light globe has a tungsten filament, which has a temperature of 2775 K when switched on.
    (a) How much radiation does the filament emit at 20 °C?
    (b) The voltage on the light globe is reduced to increase the lifetime of the filament. The temperature of the filament is now 2000 K. What is the power saving?
    (c) The voltage is now increased so that the power output is 200 W. What is the new filament temperature in Kelvin?
15. (a) A piece of iron has a yellow glow when it reaches 1150 °C. How much more energy is emitted every second at this temperature compared to when the iron glows red at 480 °C?

(b) At what temperature in degrees Celsius would the iron give off 10 times as much energy as it does at 480 °C?

Wien's Law

16. What is the wavelength of the light with the peak intensity from our solar system's closest neighbouring star, Proxima Centauri, which has an average surface temperature of 3042 K?

17. Our Sun gives off most of its light in the 'yellow' portion of the electromagnetic spectrum. Its λ_{max} is 510 nm. Calculate the average surface temperature of the Sun.

18. The Earth's surface has an average temperature of 288 K. What is the wavelength of maximum emission from the Earth's surface?

19. The human body has a surface temperature of about 37 °C.
    (a) What is the wavelength at which the human body emits the most radiation?
    (b) In what part of the spectrum is this wavelength ?

20. (a) A violet star has a spectrum with a peak intensity at a wavelength of 4×10^{-7} m. Determine the temperature at the surface of this star.
    (b) A red star has a spectrum with a peak intensity at a wavelength of 7×10^{-7} m. Determine the temperature at the surface of this star.

21. The graph above right shows how λ_{max} (the wavelength of the peak of the radiation spectrum) for a range of stars varies with their surface temperatures.
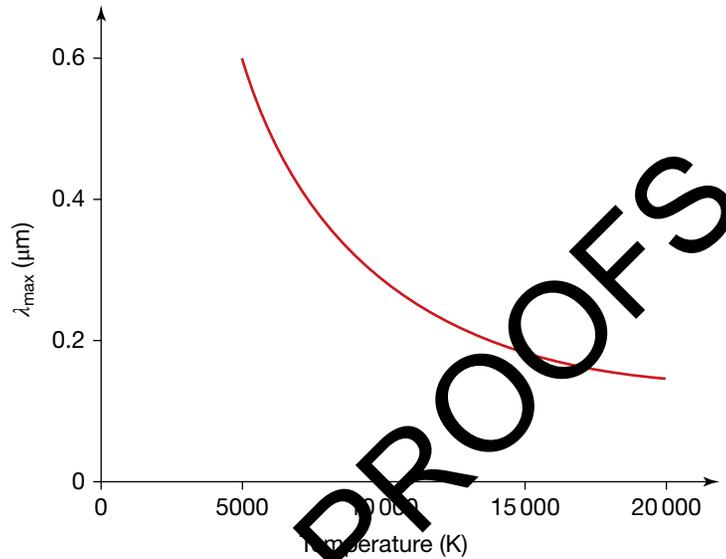
(a) Use values from the graph to confirm Wien's Law.
(b) Use the graph to estimate the surface temperature of a star whose intensity peaks at a wavelength of: (i) 0.4 μm (ii) 0.27 μm.
(c) Use the graph to estimate the peak wavelength for a star with a surface temperature of: (i) 15 000 K (ii) 5550 K.

22. Suppose the surface temperature of the Sun was about 12 000 K, rather than about 6000 K.
    (a) How much more thermal radiation would the Sun emit?
    (b) What would happen to the Sun's wavelength of peak emission?

23. Two stars have identical diameters. One has a temperature of 5800 K; the other has a temperature of 2900 K. What are the colours of these stars? Which is brighter and by how much?