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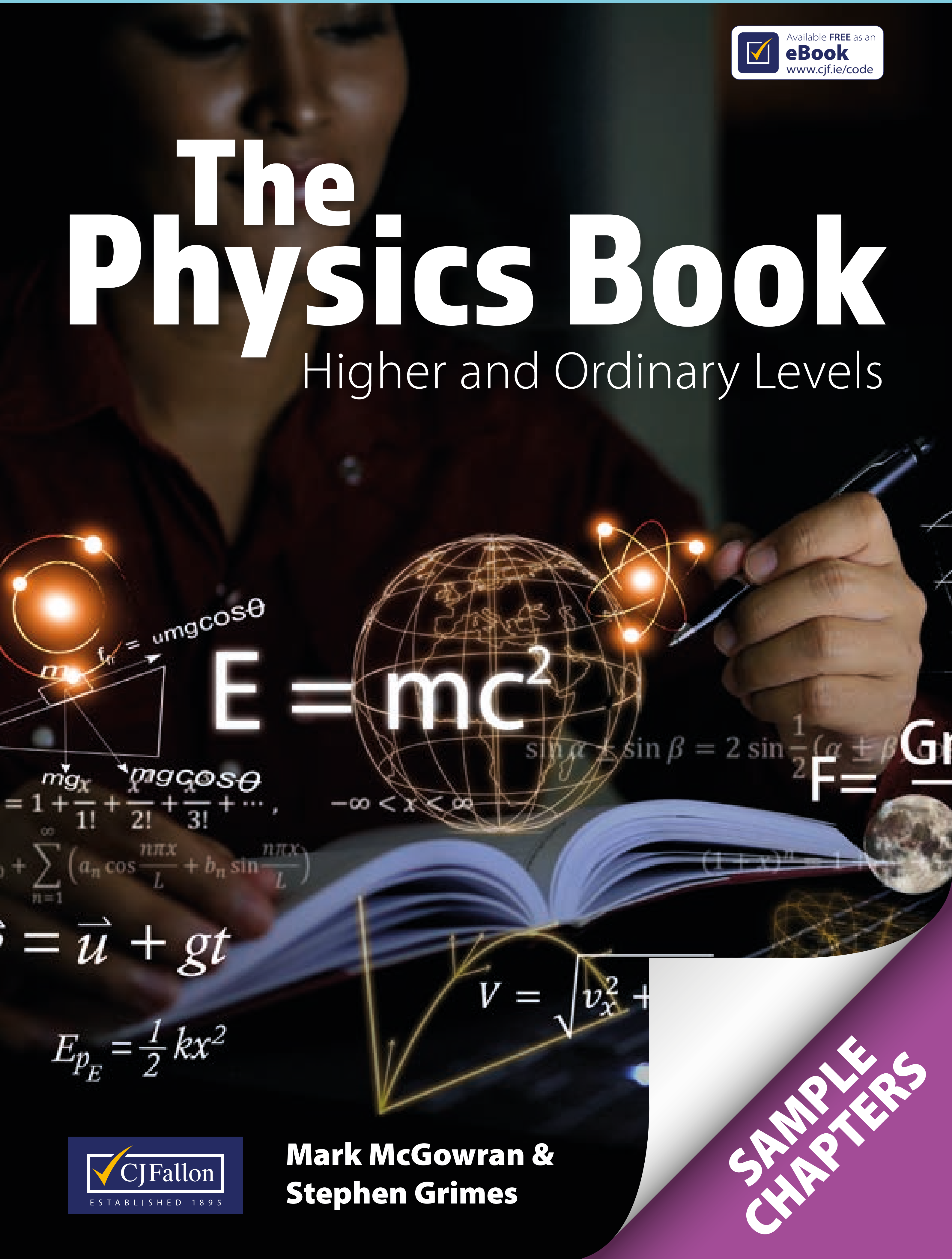
The Physics Book

Higher and Ordinary Levels



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SAMPLE CHAPTERS

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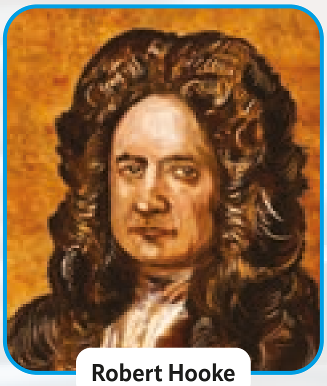
CHAPTER 10 Stretching and Compressing Objects

We have looked at how forces cause objects to accelerate, obeying Newton's laws of motion. But is there anything else that forces can do to objects? Depending on the size of the force and the object itself, a force could change its shape or deform it.

Think about when a tennis ball hits the ground during a game. If you were to take a snapshot of the moment it is in contact with the ground, its shape would be distorted. Of course, a tennis ball is an extreme example due to its composition. What about more rigid objects? They can indeed deform, but it wouldn't be as obvious to the naked eye.

The science of deforming objects or materials goes back centuries. In 1638 Galileo published *Discourses and Mathematical Demonstrations Relating to Two New Sciences* (often called *Two New Sciences*) in which he addressed the strength of materials. But it was a couple of decades later that Robert Hooke (1635–1703) carried out the most significant work in the field.



Robert Hooke

Robert Hooke was an English polymath who developed his lifelong passion for science while at Oxford University. It was here that he initially acted as assistant to Robert Boyle (1627–1635), the Irish scientist who worked on the relationship between pressure and volume in a gas. It was Hooke who developed the vacuum pump that allowed Boyle to develop the law named after him. Hooke had an illustrious career, becoming the first Curator of Experiments for the newly formed Royal Society, the United Kingdom's academy of sciences. He was the person to coin the term 'cell' through his microscopic observations of plant and animal samples, using an improved microscope he designed himself.

He was even named Surveyor to the City of London and assisted Christopher Wren (1632–1723) in rebuilding London after the Great Fire of 1666. It was his contribution to mechanics, however, that is the focus of this chapter, specifically the law of elasticity that was named for him.

Hooke's microscope

In this chapter you will learn about:

1.3 – Stretching and compressing objects
- Stretching and compressing objects
  - Hooke's law: $F = -ks$

1.4 – A work–energy model for analysing particle motion
- Work done in stretching or compressing: $E_P = \frac{1}{2}ks^2$

10.1 – Elasticity versus plasticity

Imagine an elastic band and a plastic shopping bag. What happens if you apply a force to each of them from either side of the material? They will both stretch, or their lengths will extend. But the similarity in the materials' behaviour ends there. What will happen to the elastic band and the plastic bag when we remove these forces? The elastic band will return to its original shape and length while the plastic bag will remain stretched or deformed. This is due to the different properties of the materials.

- An **elastic material** is one which returns to its original length or shape after a force is removed.
- A **plastic material** is one which remains deformed after a force is removed.

We can compress or stretch an object depending on the direction of the force we apply to it. A spring is a coil of wire that will stretch or compress when a force is applied, and then return to its original length. A spring therefore behaves **elastically**. What happens, though, if you were to apply too great a force? The spring will not return to its original length. It will have undergone **plastic deformation**. This deformation is permanent and it is because the spring has stretched beyond its **elastic limit**.

The **elastic limit** is the point of maximum stress, or force per unit area, that a material can withstand before **plastic deformation** occurs.

Provided that the force applied is kept below this limit, the material will always return to its original shape.

The question now is why does an object return to its original shape or length?

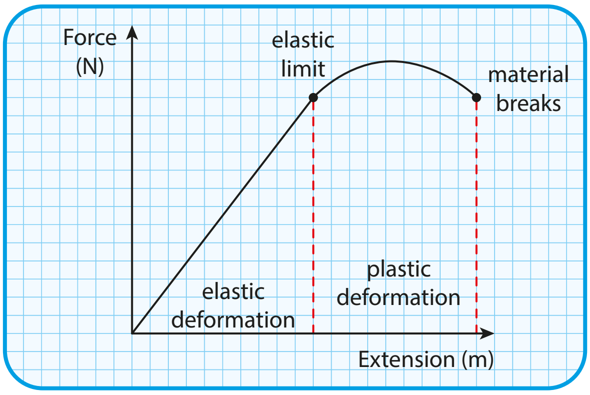


Fig. 10.1 Elastic limit

10.2 – Hooke's law

Let's consider a spring hanging freely with an original length *l* (see Fig. 10.2). if a force is applied to it, the spring will extend by a distance *s* to a new length ($l + s$). How come the spring does not continue to extend, considering that a force is acting on it? It is because there is an equal and opposite force acting on the object. This is why, when you remove the force, it will return to its original length *l*. This is the spring's **restoring force**.

What happens if you double the amount of force applied to the spring? The extension of the spring will increase. What if you now triple the force applied? The spring will extend further. Simply put, **more force means more extension**.

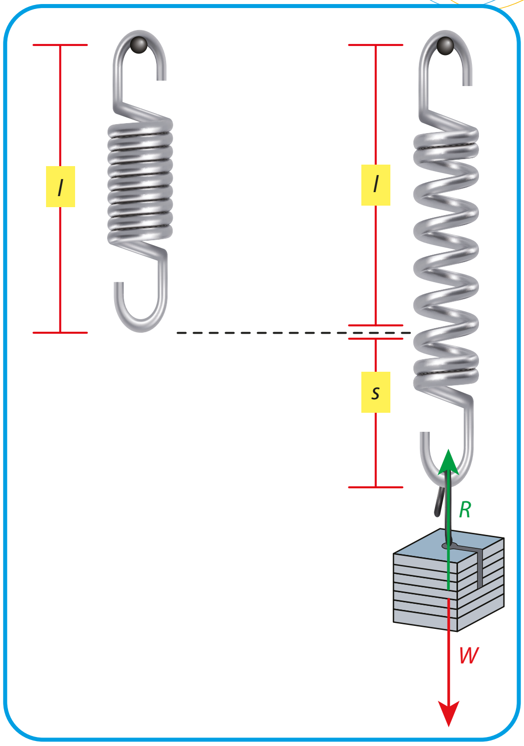


Fig. 10.2

Demo: To demonstrate how force affects the extension of a spring

Procedure

- Set up a spring hanging freely on a retort stand, with metre stick (see Fig. 10.3).
- Record the initial length of the spring with nothing attached.
- Add a weight of 1 N to the spring and record the extension in the spring.
- Repeat the previous step adding another 1 N of weight and record the new extension in the spring.

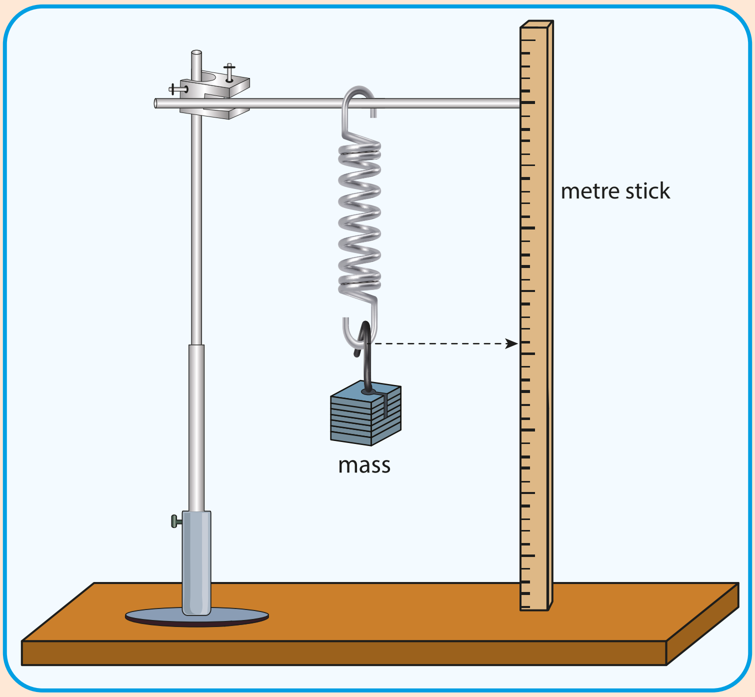


Fig. 10.3

Observation

- Extension increases linearly with force applied.

Conclusion

- The force applied to a spring is proportional to its extension: i.e. $F \propto s$.

Experiments tell us that as long as the force applied is less than the elastic limit, **Hooke's law** is obeyed.

Hooke's law states that the extension or compression of a material is directly proportional to the restoring force, provided the elastic limit is not exceeded.

Mathematically, for a material obeying Hooke's law, we see that

$$F \propto -s$$

and including a constant of proportionality, we get

$$\boldsymbol{F = -ks}$$

where: F = restoring force (N); k = force constant of the material (Nm^{-1}); s = displacement from equilibrium position (m)

The negative sign in the equation is to signify that the force is the restoring force acting on the material and always acts in a direction opposite to the extension. Remember that **the restoring force will always equal the force applied**. This allows us to use the values of applied force when carrying out calculations.

When the material is a spring, we call k the **spring constant**. It is a **measure of the stiffness of a material**. The greater the k value, the more force is required to extend the material, or the stiffer it is.

Rearranging the above equation to make k the subject, we get

$$k = \frac{F}{s}$$

and substituting the units in gives us

$$k = \frac{N}{m}$$

So k is measured in **Nm^{-1}** or **newtons per metre**.

A straight line through the origin on a graph of **force against extension** verifies Hooke's law (force is proportional to extension). If we then determine the slope of this graph, we can calculate the **force constant k** of the material.

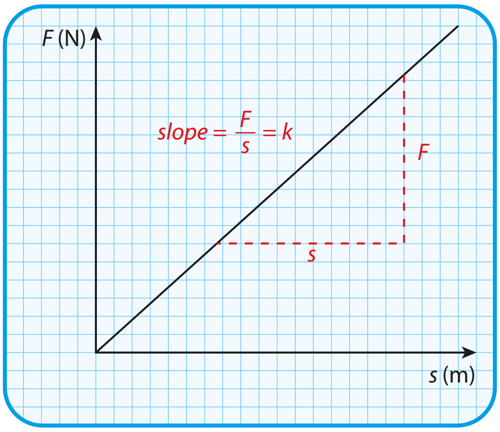


Fig. 10.4 Graph of force against extension

Applications of Hooke's law

Shock absorbers

Hooke's law can be applied to almost any object that can be elastically extended or compressed. Springs used as shock absorbers in vehicles are designed to be compressed when a force is applied and return to their original length when the force is removed. This is elastic behaviour and therefore the spring would obey Hooke's law and have its own force constant value, k.

Trampolines

Trampoline springs follow Hooke's law to create bounce. When a person jumps, the springs stretch proportionally to the applied force, storing energy that is then released to propel the jumper upwards.

Seismographs

Seismographs detect and record ground movements during earthquakes. A spring system, obeying Hooke's law, suspends a mass that oscillates in response to ground vibrations, converting the proportional displacement into data for seismic analysis.

Sample Question 10.2.1

A spring with a force constant k equal to 3 Nm^{-1} hangs freely from a clamp. A 250 g mass is attached to the bottom of the spring, resulting in the spring extending. What is the extension on the spring?

Sample Solution 10.2.1

1. Calculate the force from the weight W.

$$W = mg$$
$$W = (0.25)(9.8)$$
$$W = 2.45\text{ N}$$

2. Rearrange Hooke's law equation to make extension the subject and solve.

$$F = -ks$$
$$s = \frac{F}{k}$$
$$s = \frac{2.45}{3}$$
$$\mathbf{s = 0.82\text{ m}}$$

Sample Question 10.2.2

What is the spring constant for a spring which extends 20 cm when a force of 200 N is applied?

Sample Solution 10.2.2

$$F = -ks$$
$$k = \frac{F}{s}$$
$$k = \frac{200}{0.2}$$
$$\mathbf{k = 1000\text{ Nm}^{-1}}$$

10.2 – Hooke's law – Practice Problems

For the following problems, take g to equal 9.8 ms^{-2}

1. An unstretched spring of 60 cm has a spring constant of 200 Nm^{-1} and hangs vertically. If a downward force of 50 N is added to the spring, what is the new length of the spring?
2. An elastic system that obeys Hooke's law has an elastic constant of 3200 Nm^{-1}.
   (a) Calculate its displacement when a force of 200 N is exerted.
   (b) Calculate its restoring force when a displacement of 25 cm is made.
3. A system obeying Hooke's law has an elastic constant 1500 N/m. Find:
   (a) the force when the displacement is 5 cm
   (b) the displacement when the force is 750 N.
4. A bungee cord has a length of 16 m and a spring constant of 750 Nm^{-1}. Assuming a bungee obeys Hooke's law:
   (a) Calculate the length of the cord when a person of mass 80 kg is added.
   (b) The cord snaps if it reaches a length of 20 m. What minimum mass must be attached for this to happen (to the nearest kg)?
5. A 70 cm length of guitar G-string has a spring constant of 7500 Nm^{-1}. Calculate the length of the string when under a tension of 80 N. A guitar string will snap when stretched by a further 10% of its natural length. Does the G-string snap under 80 N?
6. A speedy blue hedgehog (mass = 35 kg) bounces onto a red spring (k = 53 478 Nm^{-1}) and compresses it by 43 cm. He is then propelled upwards, staying in contact with the spring for a total time of 35 ms:
   (a) Find the restoring force of the spring.
   (b) Find the net force acting on the hedgehog.
   (c) Find his initial velocity once he leaves the spring.
   (d) Find the maximum height the hedgehog will reach.

Worked solutions

HL

10.3 – Work done compressing and extending objects (HL only)

When a force F is applied to a material, it acts over a distance s to extend or compress the material. Therefore **work** is done in deforming the material. As long as the material stays below its elastic limit, this work can be fully recovered when the force is removed, and the material returns to its original length or shape. This means that while the material is held in a deformed state there is energy stored in the material. How do we determine the work done on a material and therefore the energy stored in it?

Let's consider a spring that extends when a force is applied, and the resulting force-extension graph.

When a force F extends a spring by a length s, there is an amount of work done W, given by the equation:

$$W = Fs$$

If we take a graph of force (F) against extension (s), then the area under the line would be equal to the total work done in extending the spring.

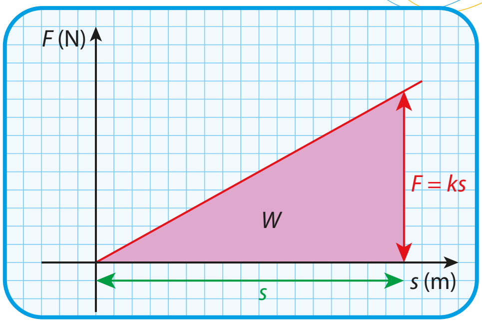


Fig. 10.5 Area under force-extension graph = work done (W)

We know that when work is done there is a transfer of energy. It was also stated above that this energy is stored in the material, and is recoverable as long as the deformation is elastic. So what form does this energy take?

Elastic potential energy

We have already looked at some potential energies and established that they are a form of stored energy due to forces exerted on an object, which can be converted to another form. Gravitational potential energy is dependent on an object's position in a gravitational field. This stored energy converts to kinetic energy when the object falls.

When a force that caused an extension on a spring is removed, the restoring force acting on it causes it to return to its original length, as long as Hooke's law is being obeyed. In simple terms, the restoring force causes an acceleration in the spring and it moves with kinetic energy. The only way for it to have that kinetic energy is if there was already an equal amount of energy stored in the spring. This is **elastic potential energy**, E_e.

Looking at the force-extension graph again, we can now say that **the area under the force-extension graph = elastic potential energy**.

Mathematically we can derive an equation for elastic potential energy:

$$E_e = \frac{1}{2}Fs$$

where F is the force applied and s is the extension of the spring.

For the spring in question, we have the relationship:

$$F = -ks$$

Substituting this into the equation for elastic potential energy we get:

$$E_e = \frac{1}{2}(ks)s$$

This simplifies to:

$$\boldsymbol{E_e = \frac{1}{2}ks^2}$$

where: E_e = elastic potential energy (J); k = elastic spring constant (Nm^{-1}); s = spring extension (m)

HL

Top Tip!

We've referred to elastic potential energy as E_e to distinguish it from gravitational potential energy E_p. It's important to note, however, that using E_p is fine in either case as both refer to **potential energy**. Also be aware that the above equation is *not* in the formulae booklet so you'll need to memorise it.

Sample Question 10.3.1

A spring of force constant *k* equal to 25 Nm^{-1} is extended by 30 cm when a force is applied. What is the elastic potential energy stored in the spring?

Sample Solution 10.3.1

1. Start with elastic potential energy equation:

$$E_e = \frac{1}{2}ks^2$$

2. Substitute in values for *k* and *s* and solve:

$$E_e = \frac{1}{2}(25)(0.30)^2$$

$$\mathbf{E_e = 1.125\ J}$$

Sample Question 10.3.2

The energy stored in a spring is 1.5 J when it is compressed by 2 mm. What is the force constant of the spring?

Sample Solution 10.3.2

1. Start with elastic potential energy equation:

$$E_e = \frac{1}{2}ks^2$$

2. Rearrange to make *k* the subject:

   First multiply both sides by two:

$$2E_e = ks^2$$

   Then divide both sides by s^2:

$$k = \frac{2E_e}{s^2}$$

3. Substitute in values and solve:

$$k = \frac{2(1.5)}{(2 \times 10^{-3})^2}$$

$$\mathbf{k = 750\ 000\ Nm^{-1}}$$

$$\mathbf{k = 7.5 \times 10^5\ Nm^{-1}}$$

10.3 – Work done compressing and extending objects – Practice Problems

1. A spring with a spring constant of 200 Nm^{-1} is stretched by 0.1 m. How much work is done in stretching the spring?
2. A toy gun uses a spring with a spring constant of 150 Nm^{-1}. If the spring is compressed by 0.05 m, how much elastic potential energy is stored in the spring?
3. A bungee cord with a spring constant of 80 Nm^{-1} is stretched by 0.4 m. Calculate the work done in stretching the bungee cord.
4. A spring with a spring constant of 250 Nm^{-1} is stretched by 0.2 m. A student wants to know the force required to stretch the spring by this amount and the work done. Calculate both.
5. A spring with a spring constant of 120 Nm^{-1} is stretched by 0.3 m. If another spring with an unknown spring constant *k* is stretched by 0.25 m and the work done is the same as for the first spring, find the spring constant *k* of the second spring.
6. An engineer is designing a spring system for a suspension bridge. The system uses a set of identical springs arranged in parallel to support a load. Each spring has a spring constant of 400 Nm^{-1}. When a test load of 800 N is applied, the springs collectively stretch by 0.1 m. Calculate the number of springs in the system and the total work done in stretching all the springs by this amount.

Worked solutions

Chapter Summary

Definitions

- The **elastic limit** is the point of maximum stress, or force per unit area, that a material can withstand before plastic deformation occurs.
- **Hooke's law** states that the extension or compression of a material is directly proportional to the restoring force, provided the elastic limit is not exceeded.

Equations (equations not in the formulae book are in **bold**)

- Hooke's law: $F = -ks$
- **Work done compressing/extending a spring: $E_P = \frac{1}{2}ks^2$**

CHAPTER 17

Heat Energy

By the end of the 19th century, it was accepted that caloric theory – the idea that heat was due to movement of an invisible fluid within substances – was obsolete. Two alternative theories that had emerged during the 18th century were calorimetry and kinetic theory.

Calorimetry focused on the measurement of heat changes in substances using a calorimeter, an insulated device used to carry out accurate measurement of heat transfer. Calorimeters are generally made of a single material of known mass and heat characteristics, and you will no doubt become familiar with them during your heat experiments.

The calorimeter is best associated with the French chemist Antoine Lavoisier (1743–94), widely regarded as the father of modern chemistry. It was Lavoisier who demonstrated the law of conservation of mass in chemical reactions, and even proved that water was a compound rather than an element. The ice-calorimeter (pictured right) was developed by Lavoisier and his colleague Laplace to investigate the heat released during respiration and combustion. Despite his contributions to scientific discovery, Lavoisier was ultimately executed in 1794 during the French Revolution, as a result of his position as tax collector for the French monarchy.

Daniel Bernoulli

The **kinetic theory** of particles or gases has some of its roots in work carried out by Irishman Robert Boyle (see Chapter 10). It was he who observed that gas pressure decreases when volume increases, implying that gas particles are in motion.

Further contributions were made by Daniel Bernoulli (1700–82), who suggested that that gas pressure is due to the particles' collisions with the walls of a container. This was a major step in linking microscopic motion to macroscopic properties like pressure and temperature. The importance of this theory was the fact that it demonstrated a link between kinetic energy and heat, thus suggesting that heat was a form of energy.

In this chapter you will learn about:

2.1 – The transfer of heat energy and temperature change

- Relationships between heat energy and temperature change
  - heat capacity: $C = \frac{Q}{\Delta\theta}$
  - specific heat capacity: $c = \frac{Q}{m\Delta\theta}$
  - latent heat: $L = Q$
  - **specific latent heat:** $l = \frac{Q}{m}$
- The concept of a heat pump

PROOFS

17.1 – Heat as a form of energy

We introduced the ideas of heat and temperature in Chapter 16. We said that heat is a form of energy and left it at that. Here is a better definition:

Heat is a form of energy that flows from a hotter object or substance to a cooler one.

But to truly understand what **heat energy** is, we must look at the particles that make up a substance or object on a microscopic level, rather than looking at the substance as a whole, or macroscopically.

A good way of visualising how heat energy works is to consider the **particle model** of matter that we discussed in the last chapter.

As a **solid** substance is provided heat energy, the vibration of the particles increases. They then reach a point where they break free from their fixed positions and become a **liquid**. Continuing to provide heat energy will cause the particles to move still faster and eventually reach a point where they will move away from one another, becoming a **gas**. The reverse will be observed when their kinetic energies decrease or the substance loses heat energy.

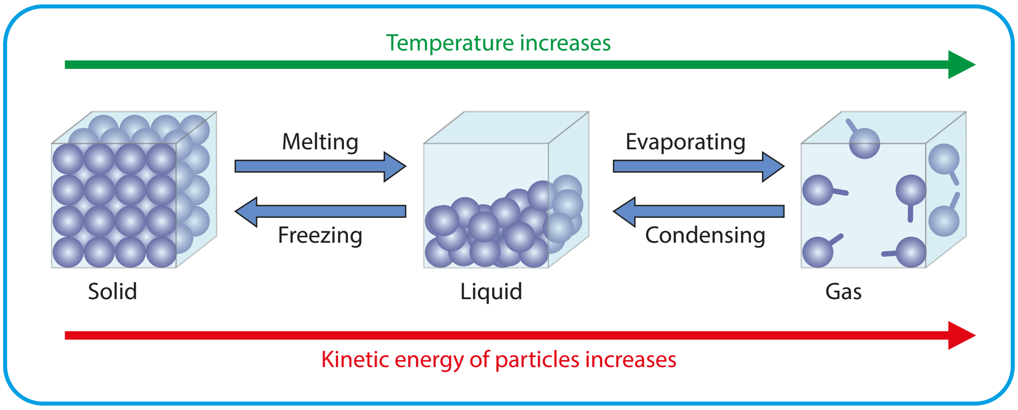


Fig. 17.1 The flow of heat energy

17.2 – Heat capacity

Imagine two beakers of water, one containing 200 ml of water and the other two litres of water (Fig. 17.2). If they were both at room temperature (approximately 20 °C) and you heated them with identical heat sources, which one will heat up more quickly? The 200 ml beaker, of course, because there is less mass that the energy needs to heat up. Now consider how much energy each beaker contains if you heat up both to 80 °C. More energy was required to raise the temperature of two litres of water, so it holds within it that amount of heat energy. So we can say the larger beaker of water has a greater **heat capacity**.

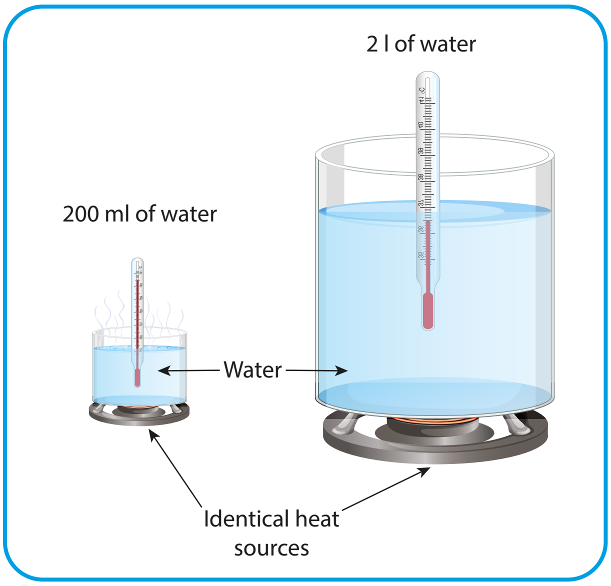


Fig. 17.2

The heat capacity of a body is the energy required to raise the temperature of the substance by 1 K.

Heat capacity is a property of a body or object rather than a substance. Both beakers contain the same substance, water, but their masses are different, so they have different heat capacities.

Heat capacity is represented by the symbol ***C***, and is measured in **joules per kelvin** or **JK^{-1}** (the number of joules required for every 1 K temperature increase).

It can be calculated from the equation:

$$C = \frac{Q}{\Delta\theta}$$

where: C = heat capacity (JK^{-1}); Q = heat energy (J); $\Delta\theta$ = change of temperature (K)

Top Tip!

Different text books use different notations to signify heat energy. Some use *Q* and others use *E*. Your formula tables use *E*. We're using *Q* here to specify that it is heat energy.

Sample Question 17.2.1

A brick has a heat capacity of 3500 JK^{-1}. How much energy is required to raise its temperature by 65 K?

Sample Solution 17.2.1

1. Determine known values:

$$C = 2500\ JK^{-1}$$

$$Q = ?$$

$$\Delta\theta = 65\ K$$

2. Choose equation and rearrange for the unknown value (Q):

$$Q = C\Delta\theta$$

3. Substitute in values and solve:

$$Q = 3500 \times 65$$

$$Q = 227\,500\ J$$

$$\mathbf{Q = 2.28 \times 10^5\ J}$$

This shows that to heat a brick by 65 °C you need to add over 200 000 joules of energy to it.

Wave Motion and Energy Transfer

PROOFS

What if we wanted two different substances to increase in temperature by the same amount? That would require different amounts of energy for different substances. This requirement is called **specific heat capacity**.

Specific heat capacity

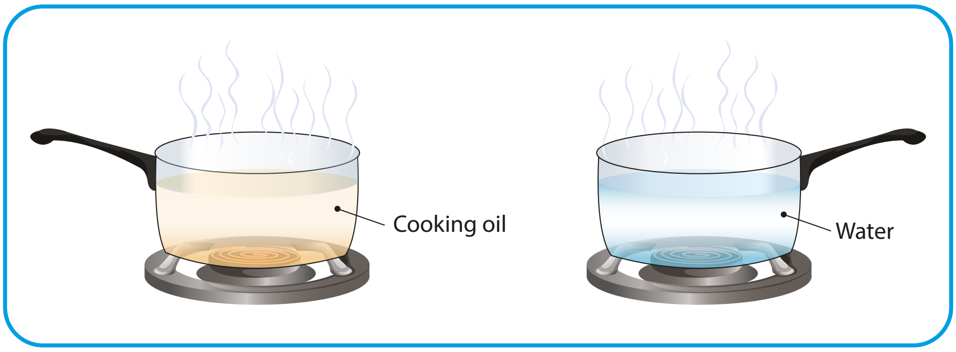


Fig. 17.3

Consider two identical copper pots, one filled with vegetable oil and the other with water (Fig. 17.3). The liquids have equal mass and the same surface area. They are both at room temperature and you apply identical heat sources to them. If the heat is applied to both for one minute, which will get hotter?

What is observed is that the oil will heat up faster, reaching higher temperatures in a shorter time. Why?

The reason is that vegetable oil has a lower **specific heat capacity**. This means that it requires less energy to increase its temperature by 1 K.

Now imagine yourself on a tropical beach in the summer. It's just after midday and the sun has been out all morning. Which is hotter, the sand or the water? The sand is much hotter to walk on. But why? They have both been in direct sunlight for the same amount of time. Sand has a lower specific heat capacity than the water so requires less energy to heat up, or by giving it the same amount of heat energy it will reach a higher temperature. What it also means is that sand will cool down much more quickly and reach a significantly lower temperature in the evening, while the water will have a similar temperature day and night.

Specific heat capacity is the amount of energy required to heat up 1 kg of a substance by 1 K.

Specific heat capacity is a property of the substance rather than the object. It shows that different substances of the same mass will require different amounts of heat energy to raise their temperature by the same amount. It is represented by the symbol ***c*** and measured in **joules per kilogram per kelvin or $Jkg^{-1}K^{-1}$**.

It must be noted that specific heat capacity only applies when there is *no change of state*.

It can be calculated using the following equation:

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

where: c = specific heat capacity ($Jkg^{-1}K^{-1}$); Q = heat energy (gained or lost) (J); m = mass (kg); $\Delta\theta$ = change in temperature (K)

This equation can be rearranged to:

$$Q = mc\Delta\theta$$

Knowing how much energy a substance can absorb or release, depending on the change in its temperature, has many useful applications.

Storage heaters – These are heaters with bricks of high specific heat capacity inside. They work by slowly heating up the bricks inside overnight when electricity is cheaper. During the day the heater is turned off and the bricks slowly release their heat into the room.

Coolants – These are generally liquids with high specific heat capacities. They absorb lots of energy from a system without a large change in temperature or change of state and then disperse it to the surroundings. For example, water is commonly used as a coolant in car engines. As the engine operates, it generates heat, and the coolant absorbs this heat, preventing the engine from reaching dangerously high temperatures.

Copper cooking pans – Copper has a low specific heat capacity. For this reason it heats up relatively quickly. When food is placed on its surface it can then quickly transfer that energy to the food, so copper is often used to make cooking pots.

Geeking Out

When pizza is cooked the crust and cheese reach the same temperature, so why doesn't the crust burn your mouth like the cheese can? Cheese has a higher specific heat capacity so it will transfer a lot more energy to your mouth than the crust will. That's why it can burn.

Substance	Specific heat capacity (Jkg^{-1}K^{-1})
Water	4180
Ice	2110
Vegetable oil	1670
Concrete	880
Glass	670
Diamond	509
Iron	450
Copper	390

Table 17.1 shows some common specific heat capacity values

Demo: To demonstrate the high specific heat capacity of water

Procedure

- Inflate a balloon with air and tie it off.
- Inflate a second balloon but also add a small amount of water to it before tying it off.
- Light a small candle or tea light and hold each balloon directly over the flame, one at a time.

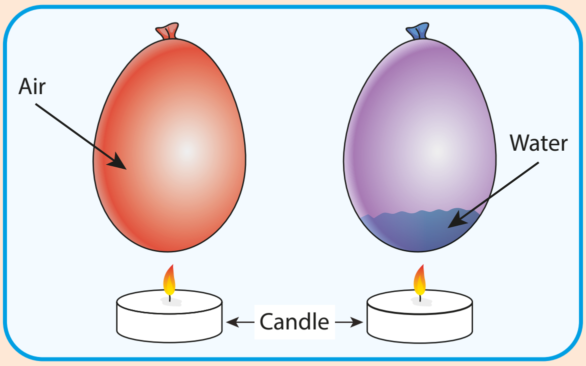


Fig. 17.4 Set-up for demo

Observation

- The balloon containing the air only will very quickly pop.
- The balloon with the small amount of water will not pop.

Conclusion

- The heat energy is absorbed by the water without much of a rise in temperature of the water or balloon. This protects the rubber of the balloon from popping.
- Water has a very high specific heat capacity.

Sample Question 17.2.2

What is the energy required to heat 1 kg of water from 23 °C to 70 °C?

Sample Solution 17.2.2

1. Determine values:

$Q = ?$ $m = 1$ kg $c = 4180$ Jkg^{-1}K^{-1} $\Delta\theta = 70 - 23 = 47$ °C

2. Choose equation and rearrange for the unknown value (Q):

$$Q = mc\Delta\theta$$

3. Substitute in values and solve:

$$Q = (1)(4180)(47)$$

$$\mathbf{Q = 196\,460\ J}$$

Sample Question 17.2.3

What is the mass of copper that will increase its temperature by 23 °C when 25 000 J of heat energy is provided to it?

Sample Solution 17.2.3

1. Determine values:
   $Q = 25\,000$ J $m = ?$ $c = 390$ Jkg^{-1}K^{-1} $\Delta\theta = 23$ °C
2. Choose equation and rearrange for unknown value (m):
$$Q = mc\Delta\theta$$
$$m = \frac{Q}{c\,\Delta\theta}$$
3. Substitute in values and solve:
$$m = \frac{25\,000}{390 \times 23}$$
$$\boldsymbol{m = 2.79\ \textbf{kg}}$$

Sample Question 17.2.4

A 500 g piece of copper is heated to 150 °C and dropped into 100 g of water at 21 °C. What will the final temperature of both the copper and water be?

Sample Solution 17.2.4

This question requires us to consider the principle of conservation of energy. When the hot copper is added to the cold water there will be an energy transfer from the copper to the water. The amount of energy lost by the copper will equal the amount of energy gained by the water.

$$Q_{copper} \text{ lost} = Q_{water} \text{ gained}$$

Substituting Q we get the equation:

$$m_{copper}\ c_{copper}\ \Delta\theta = m_{water}\ c_{water}\ \Delta\theta$$

Take all losses to the surroundings and the container to be negligible.

1. Determine values:
   $m_{copper} = 0.5$ kg $c_{copper} = 390$ Jkg^{-1}K^{-1} $\Delta\theta_{copper} = (150 - x)$ °C
   $m_{water} = 0.1$ kg $c_{water} = 4180$ Jkg^{-1}K^{-1} $\Delta\theta_{water} = (x - 21)$ °C
   Note: in the quantities above, x is the final temperature value we are solving for.
2. Choose equation:
$$m_{copper}\ c_{copper}\ \Delta\theta_{copper} = m_{water}\ c_{water}\ \Delta\theta_{water}$$
3. Substitute in values and solve:
$$(0.5)(390)(150 - x) = (0.1)(4180)(x - 21)$$
$$-195x + 29\,250 = 418x - 8778$$
$$29\,250 + 8778 = 418x + 195x$$
$$38\,028 = 613x$$
$$x = \frac{38\,028}{613}$$
$$\boldsymbol{x = 62\ \text{°C}}$$

17.2 – Heat capacity – Practice Problems

1. A metal spoon is heated from 12 °C to 74 °C. How much energy was absorbed by the spoon? (C_{spoon} = 320 JK^{-1})
2. Calculate the energy required to heat 2 kg of water from 20 °C to 80°C. The specific heat capacity of water is 4,180 $Jkg^{-1}K^{-1}$.
3. An aluminium frying pan absorbs 54 000 J of heat energy to increase its temperature from 25 °C to 75 °C. The specific heat capacity of aluminium is 900 $Jkg^{-1}K^{-1}$. Calculate the mass of the frying pan.
4. During a sunny day, 28 000 J of heat energy is transferred to 1.75 kg of sand, causing a temperature rise. The specific heat capacity of sand is 800 $Jkg^{-1}K^{-1}$. If the sand was measured to be 20 °C beforehand, what is its final temperature?
5. A heavy chilled copper spoon of mass 150 g at 5 °C is added to a cup of 300 g of warm water in a polystyrene cup at 95 °C. What is the final temperature of the mixture to the nearest degree? Assume the mass of the polystyrene cup is negligible. (c_{water} = 4180 $Jkg^{-1}K^{-1}$, c_{copper} = 390 $Jkg^{-1}K^{-1}$)
6. An aluminium calorimeter of mass 87 g is holding 101 g of chilled water at 4.1 °C. 89g of hot copper rivets at 100 °C are added to the mixture and the temperature of the final mixture is 10.3 °C . Use this information to find the specific heat capacity of aluminium. c_{water} = 4180 $Jkg^{-1}K^{-1}$, c_{copper} = 390 $Jkg^{-1}K^{-1}$)

Worked solutions

17.3 – Latent heat

Have you ever noticed how a steam burn can be much worse than a burn from boiling water, even if both are at the same temperature? When either comes in contact with skin, it cools down by transferring energy to your skin, which heats up until they reach a common temperature. This rapid gain in heat energy by the skin is what causes the burn.

We know that water and steam are the same substance (H_2O), so if they are at the same temperature they should transfer the same amount of energy to the skin. But what else has to happen to steam? It has to **condense** or change state back to a liquid state, and it is in this process that energy is released.

This hidden energy is known as **latent heat**. It is 'hidden' in the sense that it doesn't cause a temperature change but is essential for changing state.

Latent heat is the energy required to change the state of a body without a change in its temperature.

The symbol for latent heat is *L* and it is given by the equation:

$$L = Q$$

where: L = latent heat (J) and Q = heat energy (J)

In a solid we know that particles are in a fixed position and can only vibrate on the spot. As they are heated and the temperature rises, the vibrations increase. These vibrations represent the **specific heat capacity** of the solid. As the temperature continues to rise, it gets to a point where the particles' vibrations can no longer increase, so there is no further rise in temperature. Instead all energy absorbed at this point goes into breaking the strong intermolecular bonds holding the particles in their fixed position. This **melting point** is where there is a change of state **from solid to liquid**. The energy required to do this is known as the **latent heat of fusion**.

As the liquid is heated, the kinetic energy of the particles increases and they move around faster. This is observed as an increase in temperature. They are still close together as there are weak intermolecular forces still in play. But like the solid, the liquid will reach a point where it will no longer increase in temperature and the particles' kinetic energy stops increasing. At this **boiling point** all energy absorbed will go to breaking the weak intermolecular bonds. Once this is done, the particles are free to spread apart and are considered a **gas**. The energy required to complete this is known as the **latent heat of vaporisation**. The graph in figure 17.5 nicely represents this. It shows how temperature changes with an increase of energy. The diagonal lines represent an increase in temperature, while the horizontal lines represent a change of state.

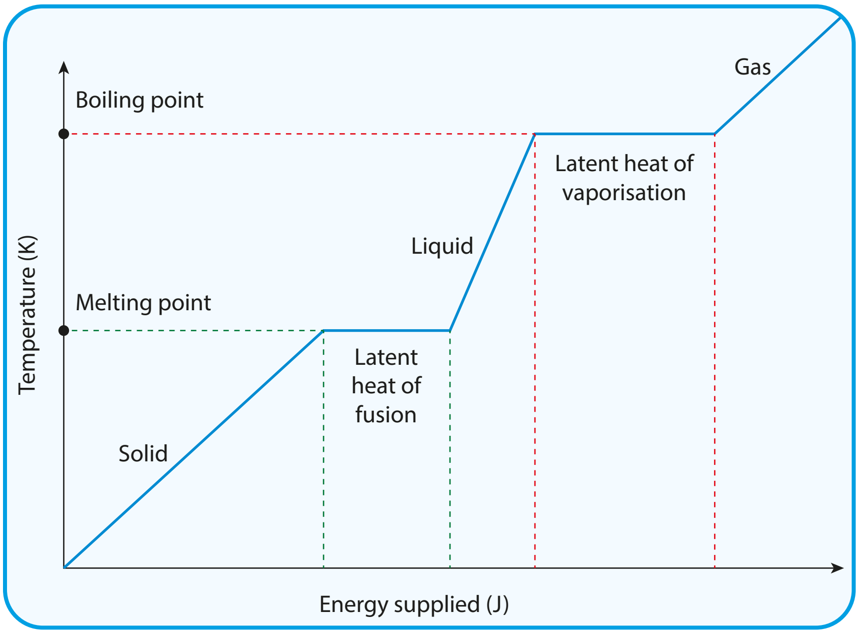


Fig. 17.5

Specific latent heat

HL

As with specific heat capacity, different substances of equal mass will require different amounts of energy to change state. That energy is the **specific latent heat** of a substance. The energy required to change ice to water will be different from that required to change water to steam.

Specific latent heat is defined as the energy required to change the state of 1 kg of a substance without a change in temperature.

The symbol for specific latent heat is *l* and it is measured in **joules per kilogram** or **Jkg^{-1}**.

HL

The value of l for a substance can be determined by the equation:

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

where: l = specific latent heat (Jkg^{-1}); Q = heat energy (absorbed or released) (J); m = mass (kg)

This is can be rearranged as in your formulae booklet:

$$Q = ml.$$

Substance	Latent heat of fusion (Jkg^{-1})	Latent heat of vaporisation (Jkg^{-1})
Water	334 000	2 260 000
Ethanol	10 800	855 000
Copper	206 000	5 069 000
Oxygen	13 900	213 000
Mercury	11 600	295 000

Table 17.2 Specific latent heat of some common substances

Where do we see latent heat in the world?

Perspiration

This is the body's method of cooling itself down. Sweat glands release sweat (liquid) onto the skin. As it sits on the skin it absorbs heat energy from it, cooling the body down. This energy is used to heat up the liquid and also evaporate it. The energy taken to evaporate is the latent heat of vaporisation.

Steaming milk

When you order a milky coffee the barista rapidly heats the milk using a steam spout. When the steam hits cold milk it cools down and condenses. In doing this it transfers heat energy to the milk, thereby heating it up.

Cooling drinks with ice

Ice will absorb lots of energy from liquid to melt without its temperature rising. This causes a quick cooling down of the beverage.

Sample Question 17.4.1

How much energy is required to change 40 g of ice at 0 °C to water at 0 °C?

(Specific latent heat of fusion of ice = 2.3×10^6 Jkg^{-1}.)

Sample Solution 17.4.1

1. Determine values:

   $Q = ?$

   $m = 0.04$ kg

   $l = 2.3 \times 10^6$ Jkg^{-1}

2. Choose equation:

$$Q = ml$$

3. Substitute in values and solve:

$$Q = (0.04)(2.3 \times 10^6)$$

$$\mathbf{Q = 92\,000\ J}$$

Sample Question 17.4.2

How much energy is now required to get the same water to steam at 100 °C?

(Specific latent heat of vaporisation of water = 3.3×10^5 Jkg^{-1}.)

Sample Solution 17.4.2

This time around we also have to consider the rise in temperature while in liquid form. This means including the specific heat capacity of water in your energy calculation.

1. Determine values:

   $m = 0.04$ kg $c_{water} = 4180$ $Jkg^{-1}K^{-1}$ $\Delta\theta_{water} = 100$ °C $L_{vaporisation} = 3.3 \times 10^5$ Jkg^{-1}

2. Determine what is gaining heat energy and what is losing heat energy and equate to ensure energy is conserved:

energy absorbed = heat gained by water to raise temperature + heat gained by water to vaporise

energy absorbed = specific heat capacity + specific latent heat

3. Choose equations for specific heat capacity and latent heat, and rearrange to make Q the subject of each equation:

$$c = \frac{Q}{m\Delta\theta} \qquad l = \frac{Q}{m}$$

$$Q = mc\Delta\theta + ml$$

4. Substitute in values and solve:

$$Q = (0.04)(4180)(100) + (0.04)(3.3 \times 10^5)$$

$$\mathbf{Q = 29\,920\ J}$$

HL

17.4 – Latent heat – Practice Problems

1. Calculate the energy required to melt 2 kg of ice at 0 °C into water at 0 °C. The latent heat of fusion of ice is 334 000 Jkg^{-1}.
2. Calculate the energy required to convert 0.5 kg of ethanol at its boiling point into vapour. The latent heat of vaporisation of ethanol is 855 000 Jkg^{-1}.
3. It takes 1 672 000 J of energy to melt a block of copper at its melting point. The latent heat of fusion of copper is 206 000 Jkg^{-1}. Calculate the mass of the copper block.
4. A 2.5 kg sample of methanol requires 2 125 000 J of energy to completely convert from liquid to vapour at its boiling point. Calculate the latent heat of vaporisation of methanol.
5. A 250 g drink at 25 °C is cooled by adding 50 g of ice at 0 °C. Assume the drink has the same specific heat capacity as water (4180 $Jkg^{-1}K^{-1}$), and the latent heat of fusion of ice is 334 000 Jkg^{-1}. What is the final temperature of the drink after the ice melts, assuming no heat is lost to the surroundings?
6. A 500 g cup of milk at 20 °C is heated to 70 °C by adding steam at 100 °C. Assume the specific heat capacity of milk is the same as water (4180 $Jkg^{-1}K^{-1}$) and the latent heat of vaporisation of water is 2 260 000 Jkg^{-1}. How much steam was added?

Worked solutions

FPO

Geeking Out

Have you ever had the chance to do the methane bubbles experiment in your science class? If you ask your teacher really nicely, they might oblige. In the experiment you ignite soap bubbles full of methane while holding them in your hand. Doing it correctly and safely, you will not get burned. Can you think of what you can put on your hands and arms to protect you, and explain how it works?

17.5 – The heat pump

We all know the role a fridge or freezer plays in our home. They keep foods fresh by keeping them at very low temperatures, increasing the time it takes for them to spoil. Have you ever put your hand at the back of the fridge? Why is it warm? How does that make the inside cold? Fridges and freezers use the principle of specific latent heat in a device called a **heat pump**.

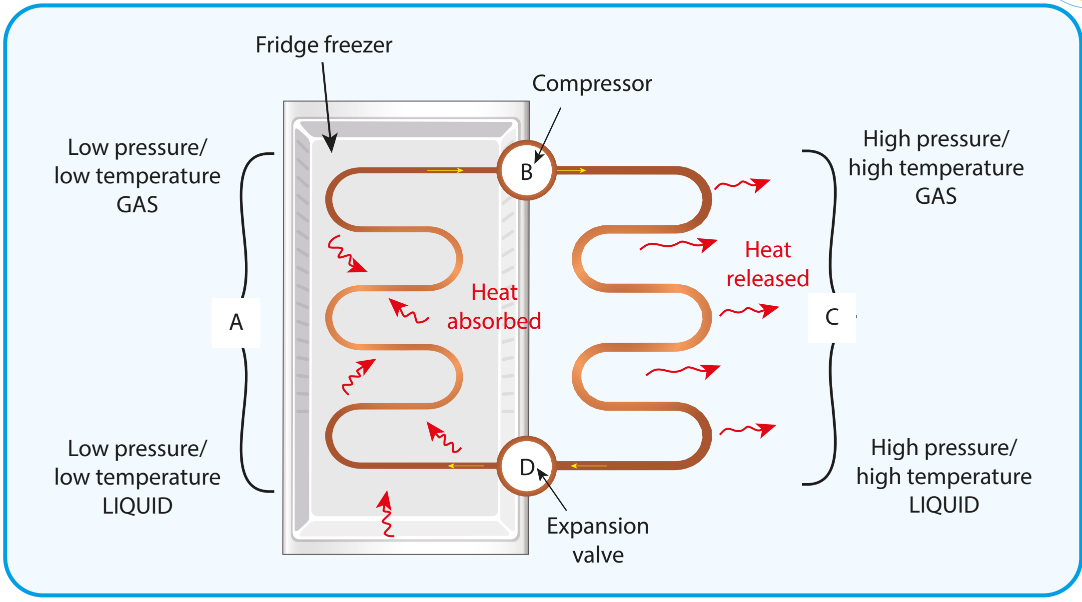


Fig. 17.6

A heat pump works on the principle of taking heat energy from one place and releasing it to another place. In the case of a fridge or freezer, the pump extracts heat from inside the appliance, thereby cooling it down, and releasing it out of the back of the appliance into the surrounding air.

The pump is a closed system of **pipes**, a **compressor** and a substance called a **refrigerant**, as seen in Fig. 17.6. The refrigerant has a **low boiling point** and a **high specific latent heat of vaporisation** value.

- The refrigerant enters the **evaporator** section (A in the diagram) in liquid form. Here it absorbs energy from inside the fridge freezer, allowing the inside to cool down and cool the contents. By absorbing this energy is vaporises into a low-pressure, low-temperature gas.
- This gas is passed through the **compressor** (B), where it becomes a high-pressure, high-temperature gas.
- From here it enters the **condenser** stage (C), where it releases the previously absorbed heat energy to the surroundings, condensing back into a high-temperature liquid.
- It is then passed through the **expansion valve** (D), where it is able to drop to a low-temperature, low-pressure liquid.
- At this point the refrigerant has done its job extracting heat energy from inside the fridge and it is cycled back around to repeat the process.

Heat pumps have applications beyond fridge freezers. More modern home-heating systems use heat pumps. They extract heat energy from outside the building and release it inside to heat the home or the water system. **Air conditioners** also use heat pumps, removing heat from inside and pumping it outside.

These modern home-heating systems reduce our reliance on oil or gas for heating. They are better for the environment and they save money on your energy bills each month. And all this is achieved by using the fact that energy is absorbed to turn a liquid into a gas and released to turn a gas into a liquid. Simple, yet incredibly useful.

Chapter Summary

Definitions

- **The heat capacity** of a body is the energy required to raise the temperature of the substance by 1 K.
- **Specific heat capacity** is the amount of energy required to heat up 1 kg of a substance by 1 K.
- **Latent heat** is the energy required to change the state of a body without a change in its temperature.
- **Specific latent heat** is defined as the energy required to change the state of 1 kg of a substance without a change in temperature.

Equations

- Heat capacity: $C = \frac{Q}{\Delta\theta}$
- Specific heat capacity: $c = \frac{Q}{m\Delta\theta}$
- Latent heat: $L = Q$
- Specific latent heat: $l = \frac{Q}{m}$ HL

Demonstrations

- To demonstrate the high specific heat capacity of water

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