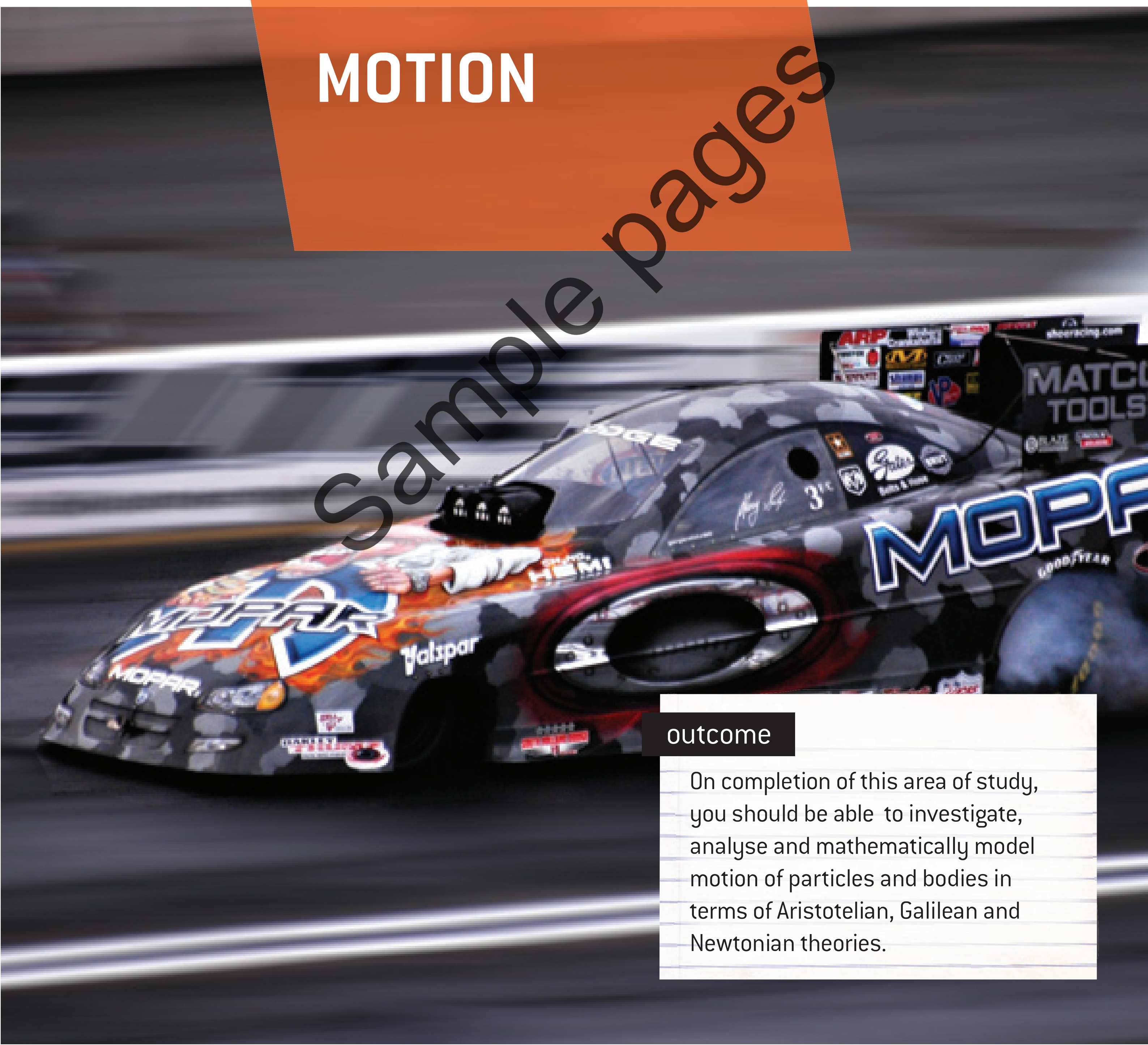
UNIT 2

Area of Study 1

MOTION



outcome

On completion of this area of study, you should be able to investigate, analyse and mathematically model motion of particles and bodies in terms of Aristotelian, Galilean and Newtonian theories.

CHAPTER 4

Aspects of motion

Pilots of fighter planes sometimes have to bail out of their aircraft at high altitude. Should this happen today, they would usually reach the ground safely. This has not always been the case, however. About 40 years ago, the United States Air Force conducted a series of experiments to investigate the design of parachutes that would return high-altitude pilots safely to the ground. Joe Kittinger, a US Air Force Captain, was part of this experiment. His contribution involved jumping out of a balloon from a height of 31 km!

In August 1960, after 18 months of preparations, Joe Kittinger took off in a helium balloon from New Mexico. He ascended for one and a half hours, eventually reaching a height of 31 km. At this altitude there was no air to breathe, the temperature was −35°C, the sky above was pitch black and he was virtually in space. He then waited at this altitude for the instruction to jump. It came after 12 minutes.

When he stepped out of the balloon's gondola, it was like falling through space. There was no sound or sensation of wind or air resistance because the atmosphere was so thin. As he rolled over to look upwards, he was amazed at how quickly he was accelerating away from the balloon. He free-fell for about four and a half minutes, reaching a maximum speed of 1150 km h^{-1}. In doing so, he became the first person to break the sound barrier without an aeroplane! Soon after this, he started to notice the effects of the atmosphere which began to slow him down. He then opened the main parachute and reached the ground 13 minutes and 45 seconds after stepping out of the gondola. A number of space entrepreneurs and extreme-sport groups are currently planning to break Kittinger's record. By 2011 there had been a number of failed attempts and so Kittinger's 50-year-old record remained intact.

The motion of Joe Kittinger as he fell—his speed, acceleration due to gravity, and the effects of air resistance—are some of the ideas that will be covered in this and subsequent chapters.

by the end of this chapter

you will have covered material from the study of movement including:

- a graphical description of motion
- instantaneous and average velocities
- motion with constant acceleration described using graphs and equations of motion
- vertical motion under gravity.

Motion, from the simple to the complex, is a fundamental part of everyday life. The motion of a gymnast performing a routine and that of a mosquito trying to avoid your desperate attempts to swat it would be considered complex forms of motion. Far simpler examples are a tram travelling in a straight line along a road, and a swimmer doing a length of a pool. In this chapter, the simplest form of motion—straight line motion—will be analysed.

In this section, terms that are useful in describing the motion of an object—**position**, **distance**, **displacement**, **speed**, **velocity** and **acceleration**—will be discussed.

Interactive

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Physics file

The centre of mass of Formula 1 cars is very close to the ground. This makes them very stable and means that they can turn corners at high speeds; speeds at which normal cars would roll over.

Figure 4.2 Formula 1 racing cars have a low centre of mass.

Centre of mass

When analysing motion, things are often more complicated than they first seem. For example, as a freestyle swimmer travels at a constant speed of 2 m s^{-1}, the trunk of his body will move forwards with this speed. The motion of his arms is much more complex: at times they move forwards faster than 2 m s^{-1} and at other times they are actually moving backwards through the water. It is beyond the scope of this course to analyse such complex motion, but we can simplify this by treating the swimmer as a simple object located at a single point—his **centre of mass**. The centre of mass is the balance point of an object. For a person, the centre of mass is located near the waist. The centres of mass of some everyday objects are shown in Figure 4.1.

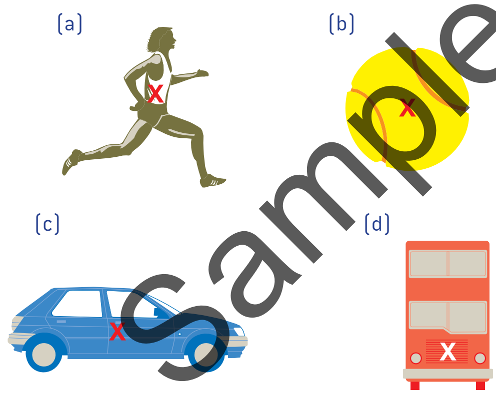

Figure 4.1 The centre of mass of each object is indicated by a cross. When analysing their motion, the total mass of each object can be considered to be located at these points.

Physics file

Table 4.1 World record distances 2011

Activity	Record (m)
Men's pole vault	6.14
Women's javelin	72.3
Paper plane flight (indoors)	58.8
Golf drive	471
Ski jump	247
Bungee jump	233
Paper clip chain	1628

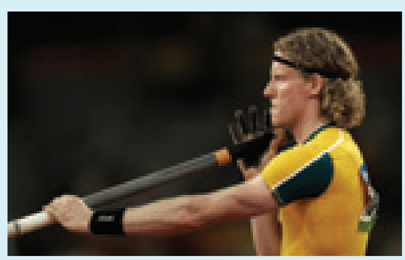

Figure 4.3 Steve Hooker from Melbourne won a gold medal in pole vault at the 2008 Beijing Olympics. His leap of 5.96 m was an Olympic record.

Position and distance travelled

Consider a swimmer, Sophie, doing laps in a 50 m pool. To simplify this situation, we will treat Sophie as a simple point object. The pool can be treated as a one-dimensional number line with the starting block chosen to be the origin. The right of the starting block is taken to be positive.

The *position* of Sophie is her location with respect to the origin. For example, her position as she is warming up behind the starting block in Figure 4.4a is –10 m. The negative sign indicates the direction from the origin, i.e. to the left. At the starting block Sophie's position is 0 m, then after half a length she is +25 m or 25 m to the right of the origin.

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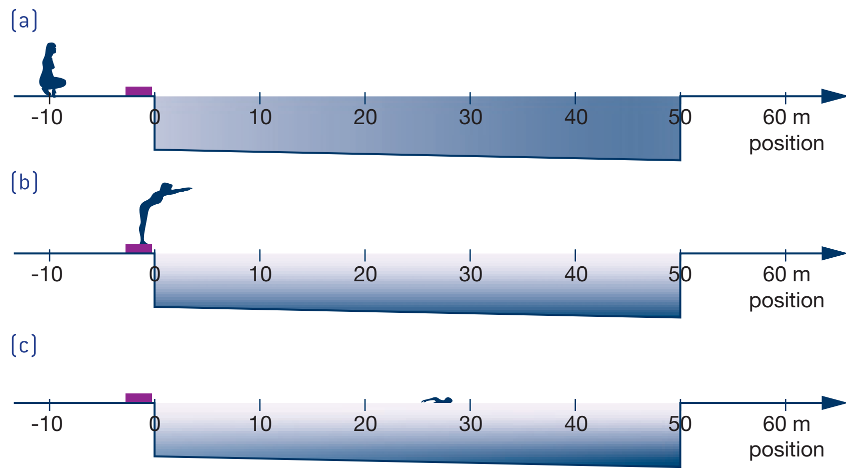


Figure 4.4 In this situation, the position of the swimmer is given with reference to the starting block. (a) While warming up, Sophie is at −10 m. (b) When she is on the starting block, her position is zero. (c) After swimming for a short time, she is at a position of +25 m.

Figure 4.5 In completing the 2008 Melbourne marathon, the athletes started just west of the MCG and ran down Beach Rd to Sandringham. They turned around and returned along Beach Rd to the MCG. Their distance travelled was more than 42 km, but their displacement was just a few hundred metres east.

Distance travelled

Distance travelled is a measure of the *actual* distance covered during the motion. For example, if Sophie completes three lengths of the pool, the distance travelled during her swim will be 50 + 50 + 50 = 150 m.

> *i* ***DISTANCE TRAVELLED***, *d*, is how far a body travels during motion. Distance travelled is measured in metres (m).

The distance travelled does not distinguish between motion in a positive or negative direction. For example, if Sophie completes one length of the pool travelling from the starting block, i.e. in a positive direction, the distance travelled will be 50 m. If she swam one length from the far end back to the start, the distance travelled will also be 50 m.

Displacement

Displacement is a term related to position and distance travelled, but it has a different meaning. Displacement, $\boldsymbol{x}$, is defined as the *change in position* of an object. Displacement takes into account only where the motion starts and finishes; whether the motion was directly between these points or took a complex route has no effect on its value. The sign of the displacement indicates the direction in which the position has changed.

> *i* ***DISPLACEMENT*** is defined as the change in position of a body in a given direction.
> Displacement $\boldsymbol{x}$ = final position − initial position
> Displacement is measured in metres (m).

Consider the example of Sophie completing one length of the pool. During her swim, the distance travelled is 50 m, and the displacement is:

$$\begin{aligned}\boldsymbol{x} &= \text{final position} - \text{initial position}\\ &= 50 - 0\\ &= 50\text{ m, i.e. 50 m in a positive direction}\end{aligned}$$

If Sophie swims two lengths, she will have travelled a distance of 100 m, i.e. 50 m out and 50 m back. However, her displacement during this swim will be:

$$\begin{aligned} \boldsymbol{x} &= \text{final position} - \text{initial position} \\ &= 0 - 0 \\ &= 0 \end{aligned}$$

Even though she has swum 100 m, her displacement is zero because the initial and final positions are the same. Displacement only considers the starting and finishing positions of the motion; it does not indicate anything about the route taken by the person or object in getting from the initial to the final position.

Scalars and vectors

Physical quantities requiring a *number only* to fully describe them are known as **scalars**. Distance is a scalar quantity. Other scalar quantities include mass, time, speed and energy.

Some physical quantities require a *number* (magnitude) and a *direction* to fully describe them. These are called *vectors*. Displacement is a vector quantity. Other vector quantities are velocity, acceleration and force. Vectors are represented in ***bold italic*** type; for example, $\boldsymbol{x}$, $\boldsymbol{v}$, $\boldsymbol{a}$. Scalars and vectors are discussed in detail in Appendix A.

Speed and velocity

For thousands of years, humans have tried to travel at greater speeds. This desire has contributed to the development of all sorts of competitive activities, as well as to major advances in engineering and design. The records for some of these pursuits are given in Table 4.2.

Speed and *velocity* are both quantities that give an indication of how fast an object moves or, more precisely, of how quickly the position of an object is changing. Both terms are in common use and are often assumed to have the same meaning. In physics, however, these terms are defined differently.

- *Speed* is defined in terms of the distance travelled and so, like distance, speed is a scalar. Thus, a direction is not required when describing the speed of an object.
- *Velocity* is defined in terms of displacement and so is a vector quantity. The SI unit for speed and velocity is metres per second (m s^{-1}); kilometres per hour (km h^{-1}) is also commonly used.

Instantaneous speed and velocity

Instantaneous speed and *instantaneous velocity* give a measure of how fast something is moving at a particular moment or instant in time. If the speedometer on a car shows 60 km h^{-1}, it is indicating the instantaneous speed of the car. If another car is detected on a police radar gun and registers 120 km h^{-1}, it indicates that this car's instantaneous speed is above the speed limit.

Table 4.2 Some world speed records (2008)

Speed activity	Record speed (m s^{-1})	Record speed (km h^{-1})
Luge	43	140
Train	161	575
Tennis serve	69.7	246
Waterskiing (barefoot)	68.3	246
Cricket delivery	44.7	161
Horse racing	19.7	71

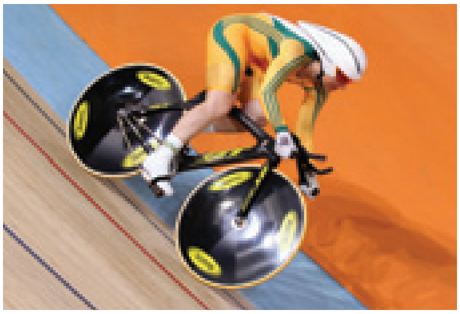


Figure 4.6 Australia's Anna Meares won a gold medal for the 500 m time trial at the 2010 Commonwealth Games in New Delhi. Her average speed was 53.3 km h^{-1}.

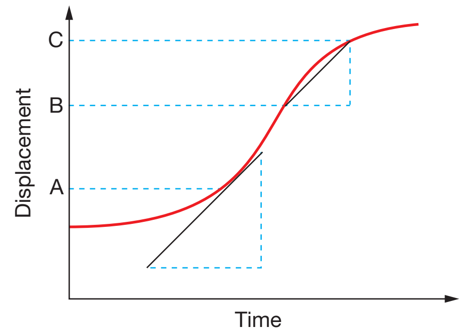


Figure 4.7 The instantaneous velocity at point *A* is the gradient of the *tangent* at that point. The average velocity between points *B* and *C* is the gradient of the *chord* between these points on the graph.

Prac 18 SPARKlab

Average speed and velocity

Average speed and *average velocity* both give an indication of how fast an object is moving over a time interval. For example, the average speed of a car that takes 1 hour to travel 30 km from Dandenong to St Kilda is 30 km h^{-1}. However, this does not mean that the car travelled the whole distance at this speed. In fact, it is more likely that the car was moving at 60 km h^{-1} for a significant amount of time, but some time was also spent not moving at all.

i ***AVERAGE SPEED*** $v_{av} = \frac{\text{distance travelled}}{\text{time taken}} = \frac{d}{\Delta t}$

Speed is measured in metres per second (m s^{-1}).

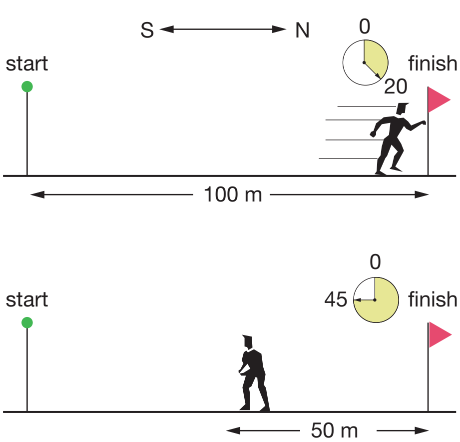
i ***AVERAGE VELOCITY*** $\mathbf{v}_{av} = \frac{\text{displacement}}{\text{time taken}} = \frac{\mathbf{x}}{\Delta t}$

Velocity is measured in metres per second (m s^{-1}) and requires a direction.

A direction (such as north, south, up, down, left, right, positive, negative) must be given when describing a velocity. The direction will always be the same as that of the displacement.

Worked example 4.1A

Consider Jana, an athlete performing a training routine by running back and forth along a straight stretch of running track. She jogs 100 m north in a time of 20 s, then turns and walks 50 m south in a further 25 s before stopping.



a Calculate Jana's average speed as she is jogging.

b What is her average velocity as she is jogging?

c What is the average speed for this 150 m exercise?

d Determine the average velocity for this activity.

e What is the magnitude of Jana's average velocity in km h^{-1}?

Solution

a Her average speed when jogging is:

$$v_{av} = \frac{\text{distance travelled}}{\text{time taken}} = \frac{d}{\Delta t} = \frac{100\text{ m}}{20\text{ s}} = 5.0\text{ m s}^{-1}$$

b Her average velocity when jogging is:

$$\boldsymbol{v}_{av} = \frac{\text{displacement}}{\text{time taken}} = \frac{\boldsymbol{x}}{\Delta t} = \frac{100 \text{ m north}}{20 \text{ s}} = 5.0 \text{ m s}^{-1} \text{ north}$$

Note that speed has been treated as a scalar and velocity as a vector.

c Jana has covered a distance of 150 m in 45 s. Her average speed is:

$$v_{av} = \frac{\text{distance travelled}}{\text{time taken}} = \frac{150 \text{ m}}{45 \text{ s}} = 3.3 \text{ m s}^{-1}$$

d She has finished 50 m to the north of where she started, i.e. her displacement is 50 m north. Her average velocity is:

$$\boldsymbol{v}_{av} = \frac{\boldsymbol{x}}{\Delta t} = \frac{50 \text{ m north}}{45 \text{ s}} = 1.1 \text{ m s}^{-1} \text{ north}$$

Jana could have ended up at the same place in the same time by travelling with this average velocity.

e Her average velocity is:

$$1.1 \text{ m s}^{-1} \text{ north} = \frac{1.1 \times 3600}{1000} = 4.0 \text{ km h}^{-1} \text{ north}$$

The magnitude is 4.0 km h^{-1}.

Acceleration

If you have been on a train as it has pulled out of the station, you will have experienced an *acceleration*. Also, if you have been in a jumbo jet as it has taken off along a runway, you will have experienced a much greater acceleration. Acceleration is a measure of how quickly *velocity changes*.

Consider the following velocity information for a car that starts from rest at an intersection as shown in Figure 4.8.

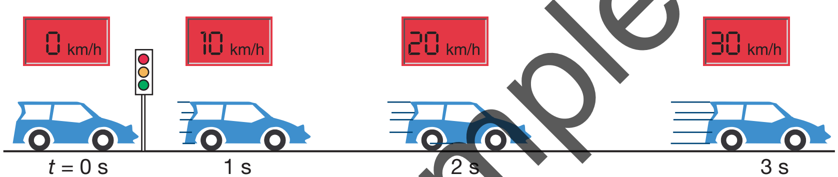


Figure 4.8 The velocity of the car increases by 10 km h^{-1} each second, and so its acceleration is said to be +10 kilometres per hour per second.

Each second, the velocity of the car increases by 10 km h^{-1}. In other words, its velocity changes by +10 km h^{-1} per second. This is stated as an acceleration of +10 kilometres per hour per second or +10 km h^{-1} s^{-1}.

More commonly in physics, velocity information is given in metres per second. The athlete in Figure 4.9 takes 3 s to come to a stop at the end of a race.

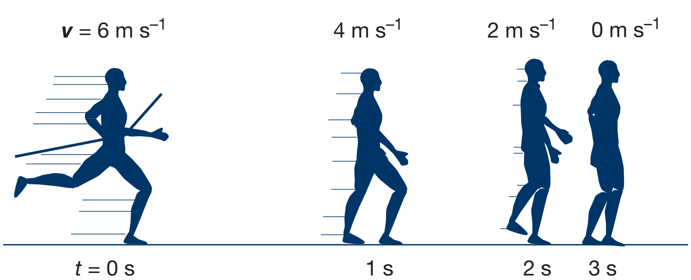


Figure 4.9 The velocity of the athlete changes by −2 m s^{-1} each second. The acceleration is −2 m s^{-2}.

Physics file

When converting a speed from one unit to another, it is important to think about the speeds to ensure that your answers make sense.

From km h^{-1} to m s^{-1}: 100 km h^{-1} is a speed that you should be familiar with as it is the speed limit for most freeways and country roads. Cars that maintain this speed would travel 100 km in 1 hour. Since there are 1000 m in 1 km and 60 × 60 = 3600 s in 1 hour, this is the same as travelling 100 000 m in 3600 s.

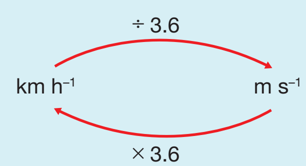
$$\begin{aligned} 100 \text{ km h}^{-1} &= 100 \times 1000 \text{ m h}^{-1} \\ &= 100\,000 \text{ m h}^{-1} \\ &= 100\,000 \div 3600 \text{ m s}^{-1} \\ &= 27.8 \text{ m s}^{-1} \end{aligned}$$

So km h^{-1} can be converted to m s^{-1} by multiplying by 1000/3600 (i.e. ÷ 3.6).

From m s^{-1} to km h^{-1}: A champion Olympic sprinter can run at an average speed of close to 10 m s^{-1}, i.e. each second the athlete will travel approximately 10 metres. At this rate, in 1 hour the athlete would travel 10 × 3600 = 36 000 m, i.e. 36 km.

$$\begin{aligned} 10 \text{ m s}^{-1} &= 10 \times 3600 \text{ m h}^{-1} \\ &= 36\,000 \text{ m h}^{-1} \\ &= 36\,000 \div 1000 \text{ km h}^{-1} \\ &= 36 \text{ km h}^{-1} \end{aligned}$$

So m s^{-1} can be converted to km h^{-1} by multiplying by 3600/1000 (i.e. × 3.6).



Each second the velocity of the athlete changes by $-2\ \text{m s}^{-1}$, and so the acceleration is –2 metres per second per second. This is usually expressed as –2 metres per second squared or $-2\ \text{m s}^{-2}$.

Acceleration is defined as the rate of change of velocity. Acceleration is a vector quantity whose direction is that of the velocity change.

A negative acceleration can mean that the object is slowing down in the direction of travel as is the case with the athlete above. What would happen to the athlete in the next few seconds if the trend continued? The athlete's velocity would be $-2\ \text{m s}^{-1}$, $-4\ \text{m s}^{-1}$ and so on. This too is a negative acceleration, which can also mean speeding up in the opposite direction.

AVERAGE ACCELERATION is the rate of change of velocity:

$$a_{av} = \frac{\text{change in velocity}}{\text{time taken}} = \frac{\Delta v}{\Delta t} = \frac{v-u}{\Delta t}$$

where v is the final velocity (m s^{-1})

u is the initial velocity (m s^{-1})

Δt is the time interval (s)

Acceleration is measured in metres per second squared (m s^{-2}).

Worked example 4.1B

A cheetah running at $20\ \text{m s}^{-1}$ slows down as it approaches a stream. Within 3.0 s, its speed has reduced to $2\ \text{m s}^{-1}$. Calculate the average acceleration of the cheetah.

Solution

The average acceleration of the cheetah is:

$$a_{av} = \frac{\Delta v}{\Delta t} = \frac{v-u}{\Delta t}$$

$$= \frac{2-20}{3.0} = -\frac{18}{3.0} = -6.0\ \text{m s}^{-2}$$

That is, each second, the cheetah is slowing down by $6.0\ \text{m s}^{-1}$.

Finding velocity changes

When finding the change in any physical quantity, the initial value is taken away from the final value. Thus, a *change in velocity* is the final velocity minus the initial velocity:

$$\Delta \boldsymbol{v} = \boldsymbol{v} - \boldsymbol{u}$$

In algebra, a subtraction is equivalent to the addition of a negative term, e.g. $x - y = x + (-y)$. The same rationale can be used when subtracting vectors. Vector subtraction is performed by adding the opposite of the subtracted vector:

$$\Delta \boldsymbol{v} = \boldsymbol{v} - \boldsymbol{u} = \boldsymbol{v} + (-\boldsymbol{u})$$

The negative of a vector simply points in the opposite direction, i.e. if $\boldsymbol{u}$ is $5\ \text{m s}^{-1}$ north, then $-\boldsymbol{u}$ is $5\ \text{m s}^{-1}$ south.

Worked example 4.1C

A golf ball is dropped onto a concrete floor and strikes the floor at $5.0\ \text{m s}^{-1}$. It then rebounds at $5.0\ \text{m s}^{-1}$.

a What is the change in speed for the ball?

b Calculate the change in velocity for the ball.

Solution

a Both the initial and final speed of the ball are 5.0 m s^{-1}, so the change in speed for the ball is:

$\Delta v = v - u = 5.0 - 5.0 = 0$

As speed is a scalar quantity, the direction of motion of the ball is not a consideration.

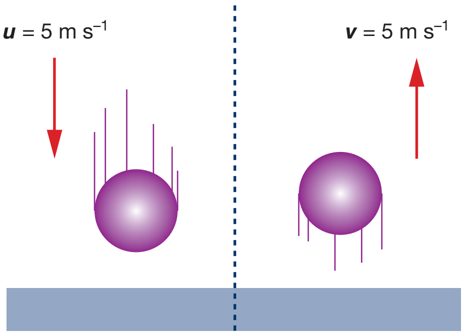
b To determine the change in velocity of the ball:

$\Delta \boldsymbol{v} = \boldsymbol{v} - \boldsymbol{u} = 5.0$ m s^{-1} up $-$ 5.0 m s^{-1} down

Let up be the positive direction, so:

$\Delta \boldsymbol{v} = +5.0 - (-5.0) = +5.0 + 5.0 = 10$ m s^{-1} up

As can also be seen in the diagram, a *vector subtraction* gives the change in velocity of the ball, in this case, 10 m s^{-1} up. Velocity is a vector quantity and the change in direction of the ball is responsible for its velocity change.



$\Delta \boldsymbol{v} = \boldsymbol{v} - \boldsymbol{u}$
$= 5\uparrow - 5\downarrow$
$= 5\uparrow + 5\uparrow$
$= \uparrow 10$ m s^{-1}
$= 10$ m s^{-1} up

Physics in action

Breaking the speed limit!

Over the past 100 years, advances in engineering and technology have led to the development of faster and faster machines. Today cars, planes and trains can move people at speeds that were thought to be unattainable and life-threatening a century ago.

The 1-mile land speed record is 1220 km h^{-1} (339 m s^{-1}). This was set in 1997 in Nevada by Andy Green driving his jet-powered Thrust SSC. The fastest combat jet is the MIG-25. It reached a speed of 3800 km h^{-1} in 1976, which is more than three times the speed of sound.

The fastest speed recorded by a train is 575 km h^{-1} (160 m s^{-1}) by the French TGV *Atlantique* in 2007, although it does not reach this speed during normal operations.

The world record speed for racing dragsters is almost as fast as this, although dragsters only race 400 m. A piston engine (as opposed to rocket-powered!) dragster can cover the 400 m in 4.4 s and reach a maximum speed of 475 km h^{-1}. It can achieve a peak acceleration of 56 m s^{-2} during its trip and a parachute has to be used to slow it down.

In the 1950s, the United States Air Force used a rocket sled to determine the effect of extremely large accelerations on humans. It consisted of an 800 m long railway track and a sled with nine rocket motors. One volunteer—Lieutenant Colonel John Stapp—was strapped into the sled and accelerated to speeds of over 1000 km h^{-1} in a very short time. Then water scoops were used to stop the sled in just 0.35 s. This equates to a deceleration of 810 m s^{-2}.

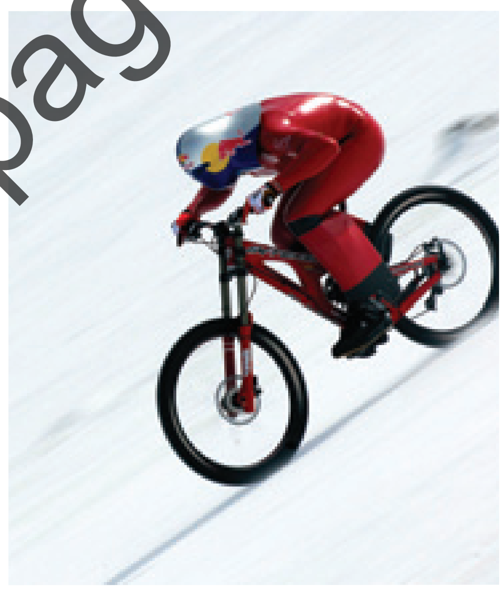


Figure 4.10 In 2007, Markus Stoeckl of Austria set a new speed record for mountain biking. He reached a speed of 210 km h^{-1} racing down a ski slope in Chile.

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Breaking the speed limit! (continued)

Table 4.3 World record times and speeds for men and women in 2011

Event	Distance (m)	Time (h:min:s)	Average speed
Men			
Running	100	0:0:9.58	$10.3\ m\ s^{-1}$
	200	0:0:19.19	$10.4\ m\ s^{-1}$
	400	0:0:43.18	$9.1\ m\ s^{-1}$
	800	0:1:41.01	$7.9\ m\ s^{-1}$
	1500	0:3:26.00	$7.2\ m\ s^{-1}$
	Marathon (42.2 km)	2:03:59	$5.6\ m\ s^{-1}$
Swimming	50 freestyle	0:0:20.11	$2.3\ m\ s^{-1}$
	1500 freestyle	0:14:34.56	$1.7\ m\ s^{-1}$
Cycling	56.4 km	1:00.00	$56.4\ km\ h^{-1}$
Downhill skiing			$251\ km\ h^{-1}$*

*Instantaneous speed.

Event	Distance (m)	Time (h:min:s)	Average speed
Women			
Running	100	0:0:10.49	$9.5\ m\ s^{-1}$
	200	0:0:21.34	$9.4\ m\ s^{-1}$
	400	0:0:47.60	$8.4\ m\ s^{-1}$
	800	0:1:53.28	$7.1\ m\ s^{-1}$
	1500	0:3:50.46	$6.5\ m\ s^{-1}$
	Marathon	2:15:25	$5.2\ m\ s^{-1}$
Swimming	50 freestyle	0:0:23.73	$2.1\ m\ s^{-1}$
	1500 freestyle	0:15:42.54	$1.6\ m\ s^{-1}$
Cycling	46.1 km	1:00:00	$46.1\ km\ h^{-1}$
Downhill skiing			$243\ km\ h^{-1}$*

*Instantaneous speed.

Figure 4.11 These photos show the face of Lieutenant Colonel John Stapp while he was travelling in a rocket-powered sled. As the sled blasted off, it achieved an acceleration of $120\ m\ s^{-2}$. The effect of this is evident on his face.

Physics in action

Measuring speed in the laboratory

A variety of methods can be used to determine the speed of an object in a motion experiment. Common techniques include ticker timers, ultrasound transducers, photogates and multiflash photography.

A ticker timer has a hammer that vibrates with a frequency of 50 Hz and produces a series of dots on a piece of ticker tape that is being dragged along by a moving body.

Since the hammer strikes the paper at regular intervals, the distance between the dots gives an indication of the speed of the body. Where the dots are widely spaced, the body is moving faster than when the dots are close together. Precise values of speed can be determined by measuring the distances between the dots. Consider the section of tape shown in Figure 4.12. The tape had been attached to a student to measure walking speed.

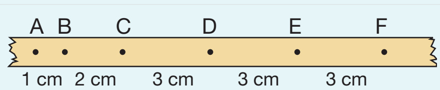


Figure 4.12 Ticker tape has been commonly used to analyse the motion of objects. If the frequency of the timer is known and the distance between the dots has been measured, the average speed of the object can be determined.

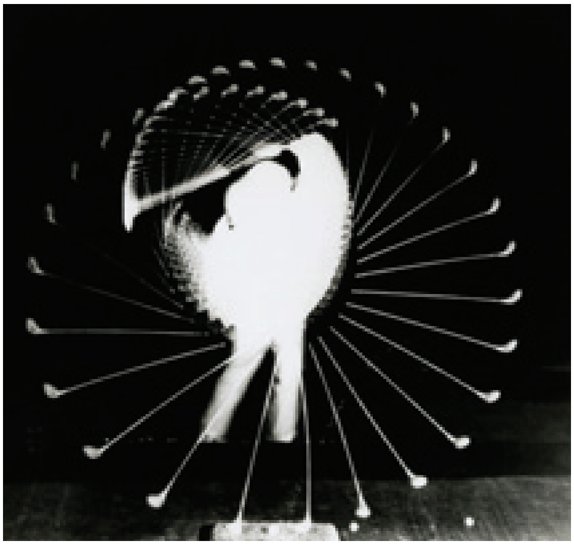


Figure 4.13 A multiflash photograph of this golf swing allows the motion of the club and ball to be analysed in detail. Three images of the ball in flight can be seen. Given that the flash frequency is 120 Hz, and the scale of the photograph is 1:50, you should be able to show that the initial speed of the golf ball is approximately 100 m s^{-1}.

Figure 4.14 Ultrasonic motion sensors can be used to analyse the movement of an object. High-frequency sound impulses are emitted from the sensor, reflected from the object and received by the sensor. A display of the motion of the object can then be seen on a computer screen.

The average speed of the student is calculated by measuring the distance travelled and taking account of the time elapsed. Since the hammer strikes the tape 50 times per second, each interval between the dots represents 1/50 s (i.e. 0.02 s). Thus the average speed between A and F, a distance consisting of five intervals, is:

$$v_{av} = \frac{\text{distance travelled}}{\text{time taken}} = \frac{12 \text{ cm}}{5 \times 0.02 \text{ s}} = 120 \text{ cm s}^{-1} \text{ or } 1.2 \text{ m s}^{-1}$$

The instantaneous speed gives a measure of the speed at one particular time. This can be estimated with reasonable accuracy by calculating the average speed for the interval one dot either side of the point being analysed. For example, the instantaneous speed at point B can be estimated by calculating the average speed between points A and C:

$$v_{inst}(\text{B}) \approx v_{av}(\text{A to C}) = \frac{\text{distance travelled}}{\text{time taken}} = \frac{3 \text{ cm}}{2 \times 0.02 \text{ s}}$$
$$= 75 \text{ cm s}^{-1} \text{ or } 0.75 \text{ m s}^{-1}$$

Multiflash photography is a useful method for analysing more complex motion. A photograph is taken by a camera with the shutter open and a strobe light that flashes at a known frequency. This is analysed in a similar manner to ticker tape. If the frequency of the flash is known, the time between each flash (i.e. the period of the flash, T) is easily found using $T = 1/f$. For example, a flash with a frequency of 20 Hz has a period of 0.05 s. By measuring the appropriate distance on the photograph, average speed can be calculated and instantaneous speed estimated.

A photogate consists of a light source and sensor that triggers an electronic timing device when the light beam is broken. Photogates are designed to measure time to millisecond accuracy, and so give very accurate speed data. Some are calibrated to give a direct reading of speed. Others will simply give a measure of the time interval between two light beams being broken. The average speed of a falling mass that passes between two photogates can be calculated by considering the distance between the photogates and the time that the mass took to pass between them.

An ultrasonic motion sensor gives a direct and instantaneous measure of the speed of a body. These devices emit a series of high-frequency sound pulses that are reflected from the moving object, giving an indication of its position. The data are then processed to give a measure of the speed. Ultrasonic sensors allow complex motions such as a sprinter starting a race, or a ball bouncing several times, to be analysed in great detail.

4.1 summary

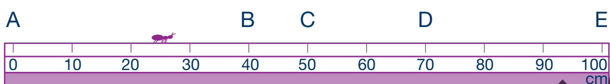
Describing motion in a straight line

- The average speed of a body, v_{av}, is defined as the rate of change of distance and is a scalar quantity:
$$v_{av} = \frac{\text{distance travelled}}{\text{time taken}} = \frac{d}{\Delta t}$$
- The average velocity of a body, $\boldsymbol{v}_{av}$, is a vector and is the rate of change of displacement:
$$\boldsymbol{v}_{av} = \frac{\text{displacement}}{\text{time taken}} = \frac{\boldsymbol{x}}{\Delta t}$$
- The SI unit for both speed and velocity is metres per second (m s^{-1}).
- Instantaneous velocity is the velocity at a particular instant in time.
- The average acceleration of a body, $\boldsymbol{a}_{av}$, is defined as the rate of change of velocity. Acceleration is a vector:
$$\boldsymbol{a}_{av} = \frac{\Delta \boldsymbol{v}}{\Delta t}$$
- Position defines the location of an object with respect to a defined origin.
- Distance travelled, d, tells how far an object has actually travelled. Distance travelled is a scalar.
- Displacement, $\boldsymbol{x}$, is a vector and is defined as the change in position of an object in a given direction. Displacement $\boldsymbol{x}$ = final position – initial position.
- Vector quantities require a magnitude and a direction, whereas scalar quantities can be fully described by a magnitude only.

4.1 questions

Describing motion in a straight line

1 A somewhat confused ant is moving back and forth along a metre ruler.



Determine both the displacement and distance travelled by the ant as it moves from:

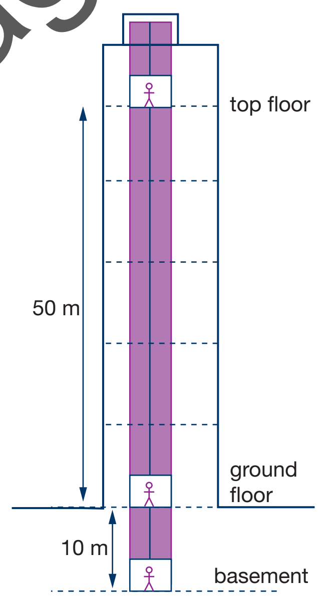
a A to B **b** C to B
c C to D **d** C to E and then to D.

2 During a training ride, a cyclist rides 50 km north then 30 km south.

a What is the distance travelled by the cyclist during the ride?
b What is the displacement of the cyclist for this ride?

3 A lift in a city building carries a passenger from the ground floor down to the basement, then up to the top floor.

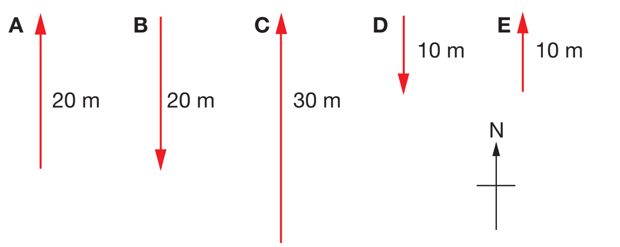
a Determine the displacement as the passenger travels from the ground floor to the basement.
b What is the displacement of the lift as it travels from the basement to the top floor?
c What is the distance travelled by the lift during this trip?
d What is the displacement of the lift during this trip?



4 Which of these physical quantities are vectors: mass, displacement, density, distance, temperature?

5 If x_1 is 20 m south and x_2 is 10 m north, which of the vectors **A–E** represents:

a $x_1 + x_2$? **b** $x_2 + x_1$? **c** $3x_2$? **d** $-x_1$?



6 Liam, aged 7, buried some 'treasure' in his backyard and wrote down these clues to help find it: start at the clothes line, walk 10 steps south, then four steps east, 15 steps north, five steps west, and five steps south.

- **a** What distance (in steps) is travelled when tracing the 'treasure'?
- **b** Where is the 'treasure' buried?
- **c** What is your displacement (in steps) after you have followed the instructions?

7 Estimate the speed:

- **a** at which you walk
- **b** of a snail crawling
- **c** of an elite 100 m sprinter
- **d** of a ten-pin bowling ball.

8 Toni rides her bicycle to school and travels the 2.5 km distance in a time of 10 min.

- **a** Calculate her average speed in kilometres per hour (km h^{-1}).
- **b** Calculate her average speed in metres per second (m s^{-1}).
- **c** Is Toni's average speed a realistic representation of her actual speed? Explain.

9 A sports car, accelerating from rest, was timed over 400 m and was found to reach a speed of 120 km h^{-1} in 18.0 s.

- **a** What was the average speed of the car in m s^{-1}?
- **b** Calculate the average acceleration of the car in km h^{-1} s^{-1}.
- **c** What was its average acceleration in m s^{-2}?
- **d** If the driver of the car had a reaction time of 0.60 s, how far would the car travel while the driver was reacting to apply the brakes at this speed of 120 km h^{-1}?

10 A squash ball travelling east at 25 m s^{-1} strikes the front wall of the court and rebounds at 15 m s^{-1} west. The contact time between the wall and the ball is 0.050 s. Use vector diagrams, where appropriate, to calculate:

- **a** the change in speed of the ball
- **b** the change in velocity of the ball
- **c** the magnitude of the average acceleration of the ball during its contact with the wall.

11 A bus travelling north along a straight road at 60 km h^{-1} slows down uniformly and takes 5.0 s to stop.

- **a** Calculate the magnitude of its acceleration in km h^{-1} s^{-1}.
- **b** Calculate its acceleration in m s^{-2}.

12 During his world record 1500 m freestyle swim, Grant Hackett completed 30 lengths of a 50 m pool in a time of 14 min 38 s.

- **a** What was his distance travelled during this race?
- **b** What was his average speed (in m s^{-1})?
- **c** What was his displacement during the race?
- **d** What was his average velocity during his record-breaking swim?

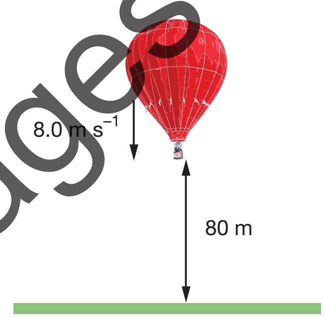
Worked Solutions

7 A book is knocked off a bench and falls vertically to the floor. If the book takes 0.40 s to fall to the floor, calculate:
 a its speed as it lands
 b the height from which it fell
 c the distance it falls during the first 0.20 s
 d the distance it falls during the final 0.20 s.

8 While celebrating her 18th birthday, Bindi pops the cork off a bottle of champagne. The cork travels vertically into the air. Being a keen physics student, Bindi notices that the cork takes 4.0 s to return to its starting position.
 a How long does the cork take to reach its maximum height?
 b What was the maximum height reached by the cork?
 c How fast was the cork travelling initially?
 d What was the speed of the cork as it returned to its starting point?
 e Describe the acceleration of the cork at each of these times after its launch:
  i 1.0 s i 2.0 s iii 3.0 s

9 At the start of a football match, the umpire bounces the ball so that it travels vertically and reaches a height of 15.0 m.
 a How long does the ball take to reach this maximum height?
 b One of the ruckmen is able to leap and reach to a height of 4.0 m with his hand. How long after the bounce should this ruckman endeavour to make contact with the ball?

10 A hot-air balloon is 80 m above the ground and travelling vertically downwards at 8.0 m s^{-1} when one of the passengers accidentally drops a coin over the side. How long after the coin reaches the ground does the balloon touch down?



Worked Solutions

Chapter review

Aspects of motion

For the following questions, the acceleration due to gravity is 9.8 m s^{-2} down and air resistance is considered to be negligible.

The following information relates to questions 1–3. During a game of mini-golf, a girl putts a ball so that it hits an obstacle and travels straight up into the air, reaching its highest point after 1.5 s.

1 Which one of the following statements best describes the acceleration of the ball while it is in the air?
 A The acceleration of the ball decreases as it travels upwards, becoming zero as it reaches its highest point.
 B The acceleration is constant as the ball travels upwards, then reverses direction as the ball falls down again.
 C The acceleration of the ball is greatest when the ball is at the highest point.
 D The acceleration of the ball is constant throughout its motion.

2 What was the initial velocity of the ball as it launched into the air?

3 Calculate the maximum height reached by the ball.

4 Theories, such as those put forward by Aristotle and Galileo, are not usually replaced unless the theory no longer works or a better theory is proposed. Discuss some of the problems with Aristotle's theories that led to them being replaced by new theories proposed by Galileo and, later, by Isaac Newton.

The following information relates to questions 5–8. The graph shows the position of a motorbike along a straight stretch of road as a function of time. The motorcyclist starts 200 m north of an intersection.

5 During what time interval is this motorcyclist:

- a travelling in a northerly direction?
- b travelling in a southerly direction?
- c stationary?

6 When does the motorcyclist pass back through the intersection?

7 Calculate the instantaneous velocity of the motorcyclist at each of the following times.

- a 15 s
- b 35 s

8 For the 60 s motion, calculate the:

- a magnitude of the average velocity of the motorcyclist
- b average speed of the motorcyclist.

The following information relates to questions 9 and 10. A skier is travelling along a horizontal ski run at a speed of 10 m s^{-1}. After falling over, the skier takes 10 m to come to rest.

9 Which one of the following best describes the average acceleration of the skier?

- A -1 m s^{-2}
- B -10 m s^{-2}
- C -5 m s^{-2}
- D zero

10 Calculate the time it takes the skier to come to a stop.

The following information relates to questions 11 and 12. An athlete in training for a marathon runs 15 km north along a straight road before realising that she has dropped her drink bottle. She turns around and runs back 5 km to find her bottle, then resumes running in the original direction. After running for 2.0 h, the athlete reaches 20 km from her starting position and stops.

11 Calculate the average speed of the athlete in km h^{-1}.

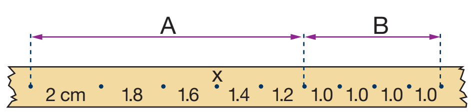
12 Calculate her average velocity in:

- a km h^{-1}
- b m s^{-1}

13 A jet-ski starts from rest and accelerates uniformly. If it travels 2.0 m in its first second of motion, calculate:

- a its acceleration
- b its speed at the end of the first second
- c the distance the jet-ski travels in its second second of motion.

The following information relates to questions 14 and 15. A student performing an experiment with a dynamics cart obtains the ticker tape data as shown below. The ticker timer has a frequency of 50 Hz.



14 Calculate the average speed of the cart during:

- a section A
- b section B
- c its total journey.

15 a What was the instantaneous speed of the cart when dot X was made?

b Calculate the magnitude of the acceleration of the cart during section A.

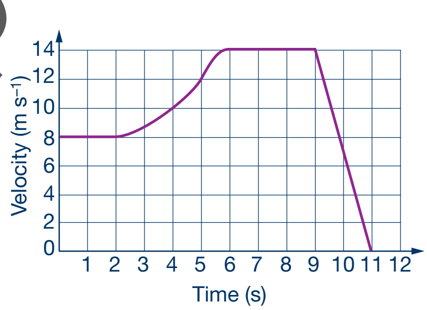
The following information relates to questions 16 and 17. Two physics students conduct the following experiment from a very high bridge. Thao drops a 1.5 kg shot-put from a vertical height of 60.0 m while at exactly the same time Benjamin throws a 100 g mass with an initial downwards velocity of 10.0 m s^{-1} from a point 10.0 m above Thao.

16 Calculate the time that:

- a the shot-put takes to reach the ground
- b the 100 g mass takes to reach the ground.

17 At what time will the 100 g mass overtake the shot-put?

The graph relates to questions 18–20. The velocity–time graph is for an Olympic road cyclist as he travels north along a straight section of track.



18 What is the average velocity of the cyclist during this 11 s interval?

19 Which one or more of the following statements correctly describes the motion of the cyclist?

- A He is always travelling north.
- B He travels south during the final 2 s.
- C He is stationary after 8 s.
- D He returns to the starting point after 11 s.

20 Calculate the acceleration of the cyclist at each of the following times.

- a 1 s
- b 5 s
- c 10 s

Worked Solutions

Chapter Quiz