

CHAPTER 7 – LINEAR MOTION AND NEWTON'S LAWS

Vectors and scalars

The ideas behind **vectors** and **scalars** are used extensively in maths and physics. A **vector** is a quantity which has **size** (called magnitude) and **direction**. By quantity we mean something like weight, displacement, velocity, acceleration, force, and momentum, all of which are vectors, and therefore have to have a direction connected to them as well as value or size. For example, a force could be 100 newtons downward (the downward specifies the direction), an acceleration could be 10 metres per second squared forwards (the forwards specifies the direction).

Usually in maths, the direction is specified by the angle to the x-axis in a graph of an arrow drawn on the graph, with the value represented by the length of the arrow (figure 7.1).

A **scalar** is a quantity which has size or value only. Quantities like mass, speed, energy, power, and length have a value only. For example, a person could have a mass of 60 kg, or an amount of 1000 joules of energy are used up when performing an exercise. No directional angle is required when talking about these quantities.

The point of this is that when more than one vector has to be taken into account, then they must be added together taking note of the direction of each vector. In figure 7.2 for example, two forces of 500 newtons are acting, the green force acts upwards, and the red force acts downwards. Because they are acting in opposite directions, they add up to nil, in other words they exactly cancel out to give zero net force.

- In figure 7.3, the vertical forces acting on the sprinter are the weight (W = force due to gravity) acting downwards, and the ground reaction force (R) acting upwards. These two forces are identical in value but opposite in direction and therefore cancel out exactly to give zero net force vertically.
- The horizontal forces are the friction force (F) acting forwards, and the **air resistance** or drag (A) acting backwards. These two forces are equal in value but opposite in direction, and hence cancel out to give zero net force acting horizontally.
- Hence relatively large forces can act, but they can cancel out because of their direction. Note that zero net force does not mean that the sprinter is stationary, see Newton's first law of motion (page 57 below).

Weight and mass

These two ideas are often confused. **Mass** is a scalar and represents the total quantity of matter in an object. **Weight** is the force due to gravity on a mass (with a direction towards the centre of the Earth) and can be calculated from the fact that the gravitational field strength at the Earth's surface is approximately 10 newtons for each kilogramme of mass. Hence if the mass of the sprinter in figure 7.3 is 50 kg, then her weight would be $50 \times 10 = 500$ newtons towards the centre of the Earth.

STUDENT NOTE

If this sprinter were to obtain astronaut status and visit the moon (where the gravitational field strength is 1.67 newtons per kilogramme), then her mass would still be 50 kg, but her weight would be $50 \times 1.67 = 83.5$ newtons towards the centre of the moon.

Distance and displacement

Distance is a scalar - usually measured in metres, **displacement** is a distance (also measured in metres) as the crow flies from start to finish of a movement. **Displacement** therefore has a value and a direction and is a **vector**.

For example, the total distance run in a 10k race will be 10,000 metres - and this is the measure which the runner will be interested in. But the displacement will be zero, since the start and finish of a 10k race are usually in the same place. Start and finish of a marathon race are often not in the same place, so the displacement between start and finish will have a value in metres and a direction. But again, runners will be interested in the distance ran, not the displacement between start and finish.

figure 7.1 – direction of a vector

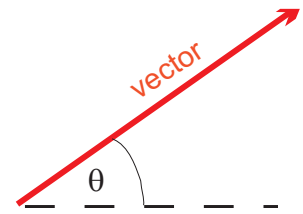


figure 7.2 – vectors cancel out

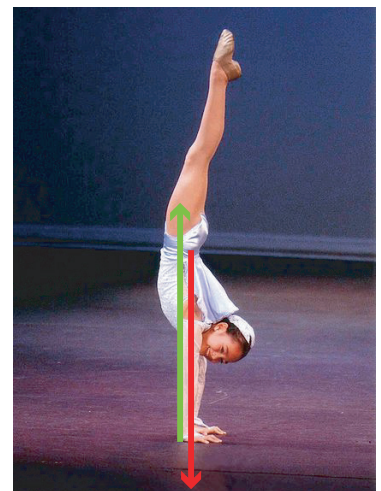
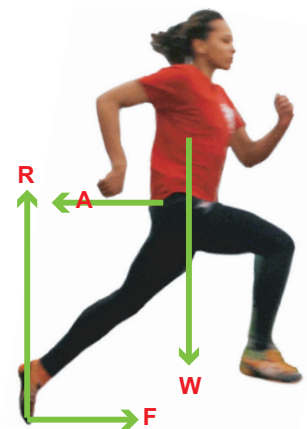


figure 7.3 – forces cancel out



Speed and velocity

Speed = $\frac{\text{distance moved}}{\text{time taken}}$ or $v = \frac{s}{t}$ unit ms^{-1}

- = scalar (no direction)
- = distance moved in 1 second

Velocity = speed in a given **direction**
= **vector**

The vector property of velocity is important because not only does it add up or cancel out a bit like the force example in figure 7.3, but it can change direction without changing value. Examples of this are a swerving rugby player, or the head of a hammer which moves in a circular path, both of whose velocity changes in direction. This means that the player or the hammer head is accelerating which means that from Newton's second law (see page 57 below) a force is required.

If you plot a graph of distance against time for a 100m sprinter, then the gradient of the graph will be a measure of speed (figure 7.4).

Acceleration

Acceleration = $\frac{\text{change of velocity}}{\text{time taken to change}}$ $a = \frac{v - u}{t}$ unit ms^{-2}

- **Acceleration** will be in the same direction as net force, and therefore acceleration is a vector (has direction).
- In the case of the swerving rugby player, the direction of acceleration is along the radius of the path of the player. This is a **radial acceleration**.
- **Deceleration** is **negative acceleration** (slowing down).

The 100 metre sprinter

A graph of velocity against time for a 100m sprinter will look as in figure 7.5. An upward slope (positive gradient) means an increase in speed hence acceleration, and a downward slope means a negative acceleration or deceleration. The gradient of the graph at any point is the acceleration, with the area under the graph being the distance moved.

- At the **start of the race** (figure 7.6a), there is a steep upwards slope which means a large acceleration. This corresponds with a large forward net force applied at the start when friction is a large forward force acting on the foot of the runner. From figure 7.6a you will see that the vertical forces cancel out, and the friction force forward is much larger than the air resistance drag force backward. This produces a large net (resultant) force forward (marked in black on figure 7.6a). This force provides forward acceleration (from Newton's second law, see page 57 opposite).
- During the **middle of the run** (figure 7.6b), the velocity time graph is almost level, which means that acceleration is almost zero, therefore forces cancel out.
- At the **end of the run** (figure 7.6c), the velocity time graph has a small negative slope, which means that the sprinter decelerates, and that therefore there is a net force backwards (shown in black).

figure 7.4 – distance time graph

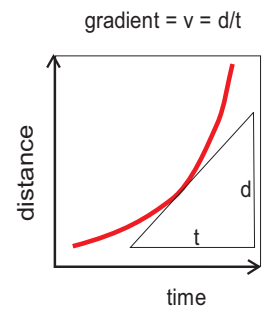


figure 7.5 – velocity time graph

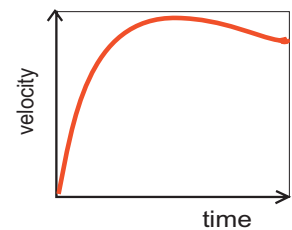
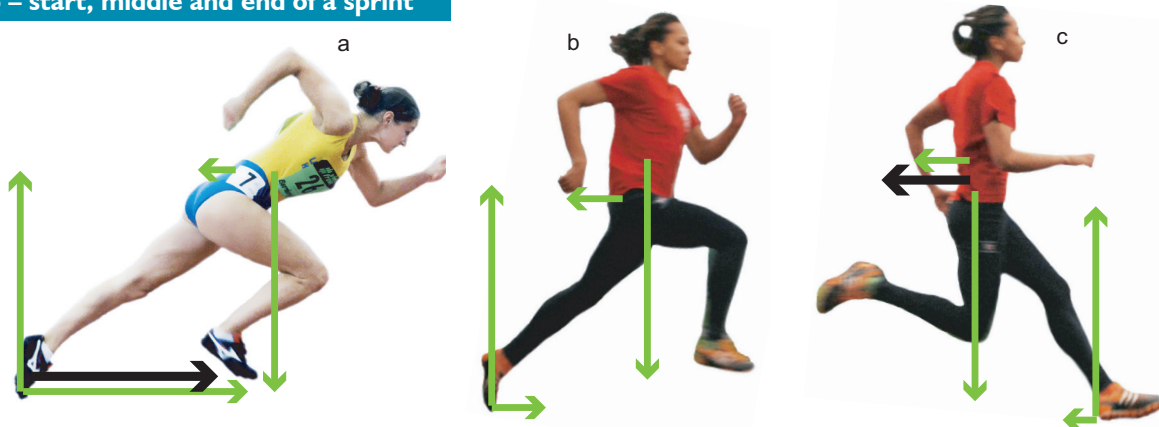


figure 7.6 – start, middle and end of a sprint



See page 58 below for the application of the concepts of momentum and impulse to the sprinter.

Newton's laws of motion

Newton's first law

Newton's first law of motion describes what happens when **zero net force** acts, which means that all forces acting must cancel out. In figure 7.6b, the forces (green arrows) **cancel out**. The vertical forces are the same size (arrows are the same length) but in opposite directions. The horizontal forces are also of the same size and in opposite directions, hence all forces cancel out.

When there is zero net force acting on an object:

- The object is **stationary**.
- **Or** the object moves at **constant velocity**.

Hence when any object moves at constant velocity, all forces must cancel out, the net force must be zero.

This law is also known as the law of **inertia**. The concept of inertia is that a massive object will remain at rest and will require a force to shift it, and once moving, will require a force to change its motion (accelerate or decelerate it).

Newton's second law

Newton's second law of motion describes what happens when a **net force acts** on a body. **A net force** produces **acceleration** or **deceleration** of the body or changes the direction of the body (swerving). In the motion of a sprinter the acceleration is produced by the net force applied, which must be forwards if the sprinter is accelerating forwards. When the sprinter **decelerates**, there is a **net force backwards**. In figure 7.6c, the vertical arrows (representing vertical forces) are the same length but in opposite directions, and hence cancel out. The horizontal forces are both acting backwards, therefore there is a net force acting backwards on her. This means that she is **decelerating** (horizontally!).

- Newton's second law also says that the bigger the **net force**, the greater the **acceleration** of the person.
- Hence a **stronger** sprinter should be able to **accelerate** out of the blocks quicker.
- However, the more mass an object has, the less the acceleration for a given force.
- Hence a heavier (more massive) sprinter will accelerate less than a lighter sprinter.

This is expressed mathematically as: $F = m \times a$ (force = mass x acceleration)

As discussed above, slowing down (**deceleration**) is also caused by force – so a bike hitting a barrier encounters a large force, large deceleration slows the bike very quickly – possibly wrecking it and hurting the rider. However, if the cyclist had applied the brakes moderately, he or she would have encountered less deceleration, taking longer to stop, but would do so safely.

Newton's third law

Newton's third law of motion describes what happens when **two bodies** (or objects) exert forces on one another. Action and reaction are equal and opposite and always occur in pairs.

Action acts on one of the bodies, and the **reaction** to this action acts on the other body. At a sprint start, the athlete **pushes back** on the blocks as hard as possible (this is the '**action**'), and the blocks **push forward** on the athlete (this push forward is the '**reaction**') - and provides forward acceleration on the athlete. In figure 7.7, a swimmer pushes backwards on the water with hands and feet (this is the force in **black** – the **action**). At the same time, the water thrusts the swimmer forward (this is the force in **red** – the **reaction**).

For **internal forces** within the body, for example in figure 7.8, the origin (O) and insertion (I) of a muscle pull in opposite directions to change the shape of the body. In this example, the **action** is the pull of the muscle (red arrow) on the origin of the muscle, and the **reaction** is the pull of the muscle (**black arrow**) at its opposite end, on the insertion. The effect is to change the shape of the person, by pulling the origin towards the insertion, and bending the limb in question.

figure 7.7 – a swimmer pushes away the water

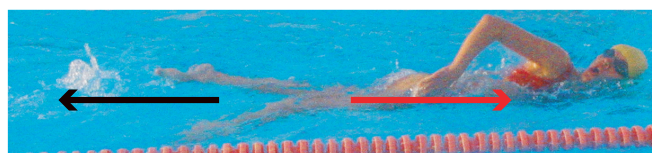
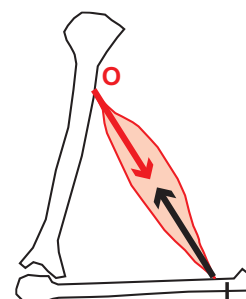


figure 7.8 – forces at origin and insertion



Momentum

Momentum is a concept derived from Newton's second law which says: **force = rate of change of momentum**
(linear) **momentum = mass x velocity**

Note that linear means in a straight line, and that momentum includes both mass and velocity.

- Hence an object which has a lot of momentum requires a lot of force to stop it, which is a good argument for fast heavy rugby players or American footballers.
- Momentum is a vector (and therefore has direction).

Impulse

Impulse is another concept derived from Newton's second law. **force = rate of change of momentum**
= $\frac{\text{change of momentum}}{\text{time taken to change}}$

Hence force x time = total change of momentum

Impulse is defined as **force x time**, therefore **impulse = total change of momentum**
unit **newton second (Ns)**

This is useful when large forces are applied for short times. Examples of the use of impulse:

- A cricket fielder catching a hard cricket ball. The incoming cricket ball will change its momentum from some high value when travelling, to zero when caught. This fixes the impulse (force x time), so if you catch the ball in a short time, a large force will be exerted, and the ball will smack the hands and hurt! If, on the other hand you let the hands go with the ball, you would increase the time over which the momentum of the ball would change, and therefore reduce the force of impact. The hands would no longer hurt!
- A bat, racquet, stick, golf club striking a ball. If you use follow-through during a strike you would increase the time of contact with the ball, therefore increase the impulse, and increase the change of momentum of the ball. The ball would therefore leave the bat with greater velocity.
- A footballer kicking a ball. Again, follow-through will increase the time of contact and therefore increase the outgoing velocity of the ball.
- The turn in the discus throw. The turn increases the time over which force is applied, and therefore increases the impulse, and increases the final momentum of the discus. This therefore increases the speed of release and the distance thrown.

Impulse and force-time graphs

The formula: **impulse = total change of momentum = force x time**

can be used to calculate change of momentum if force and time the force is acting can be measured.

Using total change of momentum = force x time

Or total change of momentum = impulse = **area under graph** of force against time

Once you have calculated the change of momentum, you can calculate the change of velocity (by dividing by the mass of the object experiencing the force).

Force-time graphs

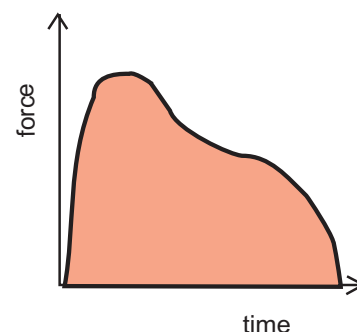
The area under this graph is the **impulse**, and in the graph in figure 7.9 of the force between foot and ground during a foot strike when sprinting, the bigger the area under the graph, the bigger the impulse, and the greater the change of momentum of the runner (and hence the greater the acceleration and therefore the change of velocity).

The sprinter

Figure 7.10 continues the theme started above of the 100 metre sprinter.

The graphs in figure 7.10 show the force-time graphs for the horizontal force acting on a single foot of a sprinter at four stages of a 100 metre sprint.

figure 7.9 – area under a force-time graph



The sprinter

- **a** when the runner is in contact with starting blocks or immediately at the start.
 - **b** when he or she is accelerating during the first 2–3 seconds of a run.
 - **c** when the runner is running at approximately constant speed during the middle of a run.
 - **d** during the slowing down at the end of a run.
- In figure 7.10a, the area under the **force–time curve** is above the horizontal axis (and hence **positive**), which means the force is acting **forwards** on the runner. The force lasts for a relatively long time, therefore the impulse is high and positive and would cause large forward acceleration and change of forward velocity of the runner.
 - In figure 7.10b, some of the area of the graph is below the horizontal axis and therefore **negative** but the **overall impulse is positive**, meaning that the runner is still accelerating forwards but not now as much as in case (a).
 - In figure 7.10c, the **positive** area above the horizontal axis is exactly **cancelled** by the **negative** area under the axis. This means that the **horizontal impulse is zero** so the sprinter would not be accelerating or decelerating and would be running at **constant speed**.
 - In figure 7.10d, the **negative** area below the axis of the graph is **bigger** than the **positive** part and hence the **overall impulse is negative**. This means that the runner will be experiencing an overall **force** (averaged over the stride) **backwards** and hence would be **decelerating** or losing speed.

In Figures 7.10 b, c and d, the parts of the graphs which show a negative impulse (area below the horizontal axis of the graph) correspond to the situation where the foot placement is in front of the runner's centre of mass and so exerts a backwards force for a short time. This is immediately followed by the centre of mass moving forward over the contact foot which then applies a forward force on the runner and hence a positive impulse for the latter part of the foot contact.

figure 7.10 – horizontal foot impulse during a sprint

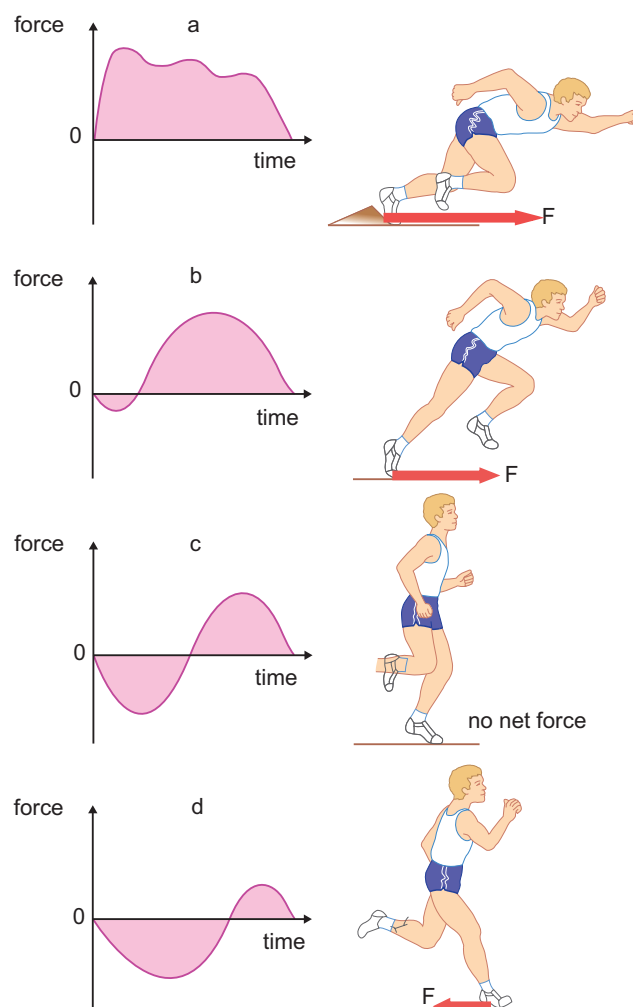


Table 7.1 – data for a 200 metres sprint

speed/ms ⁻¹	time/seconds
0.0	0
6.0	1
7.5	2
8.2	3
8.4	4
8.5	5
8.5	7
8.4	8
8.3	10
8.2	13
8.1	18
8.0	22

Practice questions

- 1) Table 7.1 shows the speed of a 19 year-old male sprinter during a 200 m race.
- Plot a graph of speed against time during this race. When does he reach maximum speed and what happens to his speed between 8 and 22 seconds? 7 marks
 - Use the graph to establish his speed at 0.5 seconds and 1.5 seconds and calculate the average acceleration between 0.5 and 1.5 seconds. 3 marks
 - Successful games players are often able to change their velocity rapidly in the game situation. Explain the biomechanics behind this ability using examples from a game of your choice. 6 marks

- 2) a) A sprinter uses her calf muscles to push on the blocks at the start of a run. Explain, using Newton's Laws, how this enables her to accelerate forwards out of the blocks. 3 marks
- b) If the resultant forward force was 300 newtons and the runner's mass was 60 kg, what would be her acceleration? 2 marks
- c) What would be the speed of the runner after 1.5 seconds, assuming that the acceleration is the same over that period of time? 2 marks
- d) A squash player drives forward into a forehand stroke. Show how Newton's third law of motion explains his ability to do this. 3 marks
- e) Explain why the turn in the discus throw produces greater horizontal range than the standing throw. 3 marks
- 3) a) What characterises a vector quantity? 2 marks
- b) Figure 7.11 shows the forces acting on a runner at the start of a race. Use a vector diagram to show how you could work out the resultant force acting. 3 marks
- c) Sketch a pin man drawing of a person standing still showing all the forces acting on him. 2 marks
- d) Sketch a second diagram showing the vertical forces acting on a basketballer just before take-off while performing a jump shot. Represent the relative sizes of any forces you show by the length of the force arrows on your diagram. 2 marks
- e) Use this second diagram and your understanding of Newton's laws of motion to explain why the basketballer is able to take off. If the vertical upward ground reaction force on him is 2000 N, and his weight is 800N, estimate the net upward force acting on him. 4 marks
- 4) The four man bobsleigh develops a large momentum during the first few seconds of its run.
- a) Explain the meaning of the term momentum, and explain why the four man bobsleigh travelling at a speed of 28 ms^{-1} has a different momentum to a skier moving at the same speed. 2 marks
- b) Explain using Newton's laws of motion how the bobsleigh acquires its large momentum during the first part of a run. 4 marks
- 5) The follow-through is an important aspect of a forehand ground stroke in tennis.
- a) Sketch a graph of the force applied by the racquet (y axis) against time (x axis). Show the effect of a follow-through on your graph. 2 marks
- b) Explain how the use of a follow-through would affect the motion of the ball. 4 marks
- 6) a) In a tennis match, the ball travels towards a player at 35 ms^{-1} . The ball has a mass of 80 g and the racket head has a mass of 0.6 kg. The racket head moves towards the ball at 10 ms^{-1} . Calculate the momentum of the racket and the ball before contact. 3 marks
- b) If the player stops the racket moving on contact with the ball, calculate the velocity of the ball after contact. 3 marks

figure 7.11 – forces acting on a runner

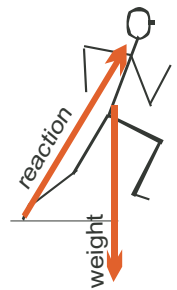
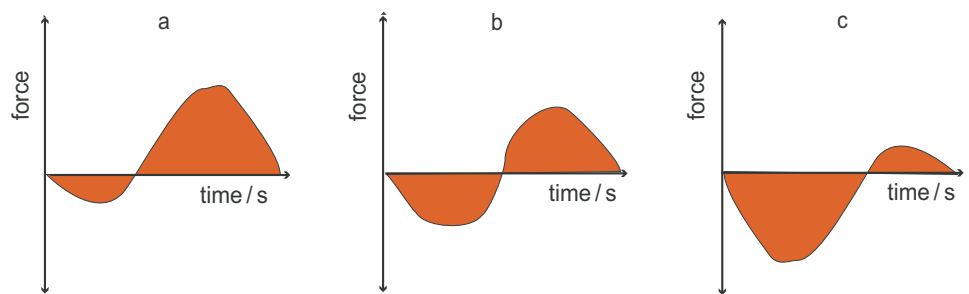


figure 7.12 – force acting on a sprinter's foot



For each graph, describe the resultant impulse force and the motion that occurs.

6 marks