UNIT

2

Newton's Second Law of Motion

LEAD-IN

1 Working in groups of three or four, state whether the following sentences are *true* or *false*, and correct the false ones.

1 While you are travelling in the back seat of a car, the driver turns suddenly and you slide away from the direction in which the car is turning. You move as a result of a force that acts upon your body. T F

2 A parked car is hit from behind in a traffic accident. If the car is large, the passengers will suffer less whiplash damage. T F

3 Before opening their parachutes, skydivers often spend time in freefall, accelerating more and more until they reach their maximum speed and a constant velocity. T F

2 Match the terms (1-6) to their corresponding definitions (a-f).

☐ 1 Free-body diagram

☐ 2 Resultant force

☐ 3 Vector equation

☐ 4 Trajectory

☐ 5 Acceleration

☐ 6 Vector components

a The sequence of positions followed by an object in motion.

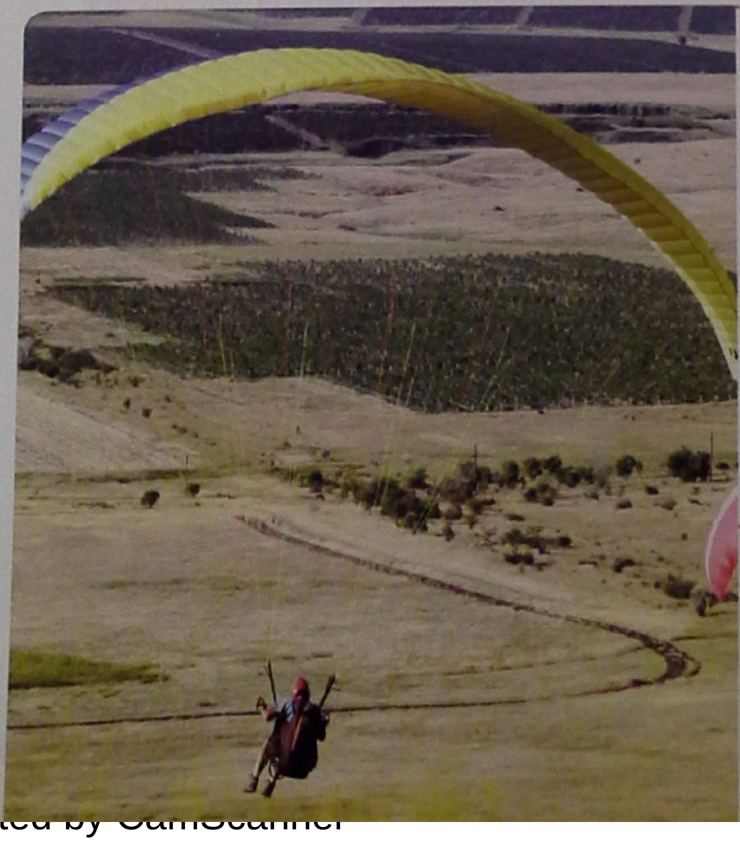
b The projection of a vector in a direction. Vectors are usually projected in the positive *x* and *y* directions of a Cartesian reference frame. A single vector is equivalent to the vector sum of its *x* and *y* components.

c The rate of change of velocity over time.

d A sketch representing all forces acting upon the object, which is represented as a point. It doesn't show forces that the object exerts on its surroundings.

e An equation involving vectors.

f The vector sum of all forces acting upon an object. The external effect it has upon the object is the same as the effects of all the forces acting upon the object combined.



SKYDIVING

The history of **skydiving** begins with Leonardo da Vinci, who had the idea that an inverted cone would slow the fall of a body immersed in a fluid. This principle is also relevant to his studies of flight. Later on, Andre-Jacques Garnerin made the first successful parachute jump from a hot-air balloon in 1797. In World War I parachuting technology was used exclusively for emergency purposes, but went on to assist in deploying soldiers to battlefields in World War II. Skydiving later became a recreational activity and a competitive international sport in 1952. A typical jump is from an altitude of 1,000 to 4,000 metres.

READING AND LISTENING

Newton's Second Law of Motion

Introduction

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Newton's first law of motion deals with bodies that are motionless or moving at a constant velocity. You know that both conditions are met if net force is equal to zero, but what happens if it isn't?

Imagine that you are sailing downwind, and can feel the wind on your back. You know that the wind is powering the boat, and that the stronger the wind blows, the more quickly the boat sails. Similarly, if you are taking a penalty for your soccer team, you know that the ball will accelerate more rapidly if you kick it harder.

These are examples of forces which act in the direction of motion and increase velocity in the direction of motion. Conversely, if a net force acts contrary to the direction in which an object is moving, its velocity will decrease. When a force acts against the direction of an object's motion, it *decelerates*. If you slide an object along a table, the force of friction, which always acts in the direction opposite to motion, slows it to a stop.

COMPREHENSION QUESTIONS 1

An object is moving at a constant speed in a straight line. What happens to the object if...

1. you increase the magnitude of the force **acting in** the direction of motion?
2. you increase the magnitude of the force **acting against** the direction of motion?

Expressing Newton's Second Law

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Newton's second law of motion states that:

> when a nonzero resultant force (F) acts upon an object, the object undergoes an acceleration (a) equal to the ratio between the resultant force and the mass (m) of the body.

This law can be expressed with the following equation:

$$\vec{a} = \frac{\Sigma \vec{F}_e}{m} \quad (2.1)$$ which is equivalent to: $$\Sigma \vec{F}_e = m \cdot \vec{a} \quad (2.2)$$

where $\Sigma \vec{F}_e$ indicates the sum of all external forces applied to an object, expressed in N (newtons), a is the object's acceleration measured in m/s^2, and m is the mass of the body in kg.

So, a nonzero net force acting upon an object doesn't cause motion: it causes a variation in velocity which is measured as acceleration. The arrows above 'force' and 'acceleration' indicate that both are vectors, and equation 2.1 shows you that acceleration is a vector with the same direction as the resultant net force. It also shows you that its intensity is equal to the ratio between the net force and the mass of the object. Note that equation 2.2 is a vector equation, and is therefore equivalent to the following three component equations:

$$\Sigma F_{e,x} = m \cdot a_x \qquad \Sigma F_{e,y} = m \cdot a_y \qquad \Sigma F_{e,z} = m \cdot a_z$$

Note that if you apply a force F to an object at rest on a frictionless surface, it undergoes an acceleration a (see eq.2.1), whereas if you apply the same force F to another object which has twice the mass,

COMPREHENSION QUESTIONS 2

Answer the following questions.

1 You see an object that isn't accelerating. Is it possible that only one force is acting upon it?
2 What does a nonzero net force acting on an object do to it?
3 What's the difference between the final three equations on page 15?

its acceleration is $a/2$. If the mass of the object is half that of the first object, the acceleration is $2a$. Thus, Newton's second law of motion can be read as: *"The acceleration of an object moving in an inertial reference frame is proportional to the net force acting on it and inversely proportional to its mass."*
Mass is therefore a measure of the inertia of an object (i.e. the tendency of an object to remain motionless if it is at rest or to oppose changes in its velocity). So, the greater the mass of an object, the greater the force necessary to make it accelerate. In other words, it will be harder to move it from rest and harder to stop if it is moving.

WATCH OUT!

You will probably have read the following sentence somewhere: *"the weight of an object is 2 kg"*. It's important to remember, however, that *mass* and *weight* are two different quantities. The weight of an object is equal to the magnitude of the gravitational force exerted upon it, and it varies with location. The mass of an object is a scalar quantity and an inherent property, and it therefore doesn't depend on external conditions. A typical set of bathroom scales uses kilograms, even though the kilogram is a unit of mass, not a unit of force.

The Motion of a Projectile

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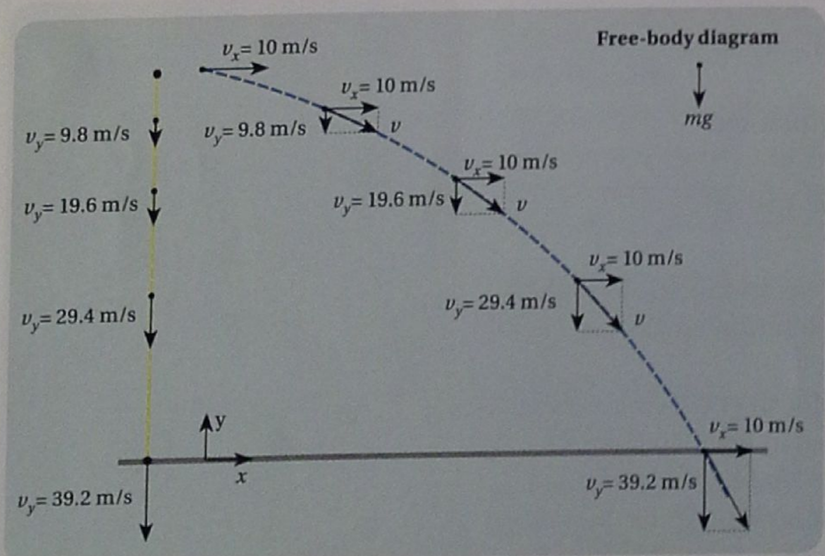
There are plenty of examples of Newton's second law of motion. You can find them by simply looking around you!

3 Discuss the following question with your partner.

A tennis ball at rest is dropped onto the ground. At the exact same moment, another ball is thrown horizontally from the same height as the first ball. Ignoring the effect of air friction, which ball hits the ground first?

- ☐ A The ball at rest hits the ground first.
- ☐ B Both balls hit the ground at the same time.
- ☐ C The ball thrown horizontally hits the ground first.

In order to understand which answer is right, see the following diagram:



↑ There are two balls in the diagram. The yellow dashed line indicates the path of the vertically dropped ball, and the blue line is the trajectory of the horizontally thrown ball. Velocity vector components are shown for the second case.

Galileo was the first person to study and describe projectile motion accurately, and his hypothesis was that all motion could be described by analysing its horizontal and vertical components separately. The resultant motion is, moment by moment, the vector sum of the two velocity components.
The diagram shows the ball that drops travelling at an increasing vertical velocity. The ball thrown horizontally, however, proceeds at such a speed that the x-component *is constant* but the y-component increases, resulting in a parabolic trajectory. In order to understand what happens in each case, note that the only force that acts on the balls is gravity, directed downward.
The ball that drops vertically has no initial velocity in any direction. According to Newton's second law, the action of the gravitational force upon it causes the vertical velocity to increase, thus producing a constant acceleration in the vertical direction only:

$$\vec{a} = \frac{\Sigma \vec{F}_e}{m} = \frac{mg}{m} = g = 9.81\ \frac{\text{m}}{\text{s}^2}$$

In the case of the second ball, you have to distinguish between [1] .... In the [2] .... direction there is no difference between the two balls. The only force acting vertically upon each ball [3] ...., which is the same in both cases. [4] ...., in the horizontal direction the thrown ball [5] .... 10 m/s.

As [6] .... forces acting in the horizontal direction, motion along the *x* direction follows [7] ....: when there is no net force acting in a direction the object remains still if it is still, but if it has an initial velocity and a direction, [8] ....
[9] ...., the motion of the ball thrown horizontally has [10] ....: the horizontal component v_x, which remains [11] .... and is [12] ...., and the vertical component v_y, which [13] .... equal to g. The vector sum of the uniform [14] .... and the accelerating [15] .... is the projectile's trajectory, which is tangential to the velocity vector at any instant.

Because the vertical motion of the two balls is identical, the result of this example (as predicted by Galileo) is: *an object thrown horizontally will reach the ground at the same time as an object dropped vertically.*

LISTENING ACTIVITY

With your partner, consider the gaps in the text to the left. Try to guess the missing words in each space, or what kind of words (nouns, verbs, connectors, etc.) might be used to fill them. When you have finished, listen to the text and copy what you hear. Were they correct?

COMPREHENSION QUESTIONS 3

Answer the following questions.

1 Does the vertically dropped ball move at a constant speed? Why, or why not?
2 Why doesn't the horizontally thrown ball accelerate in the *x*-direction?
3 If you test Galileo's idea by standing on the pavement and dropping one ball and throwing another downwards at the same moment, do you think you will observe them reaching the pavement simultaneously? Explain your answer.

PRACTICE

4 Fill in the gaps with the appropriate words or expressions.

which	resultant
mass	acceleration
constant	vector
variable	direction
whether	equal to

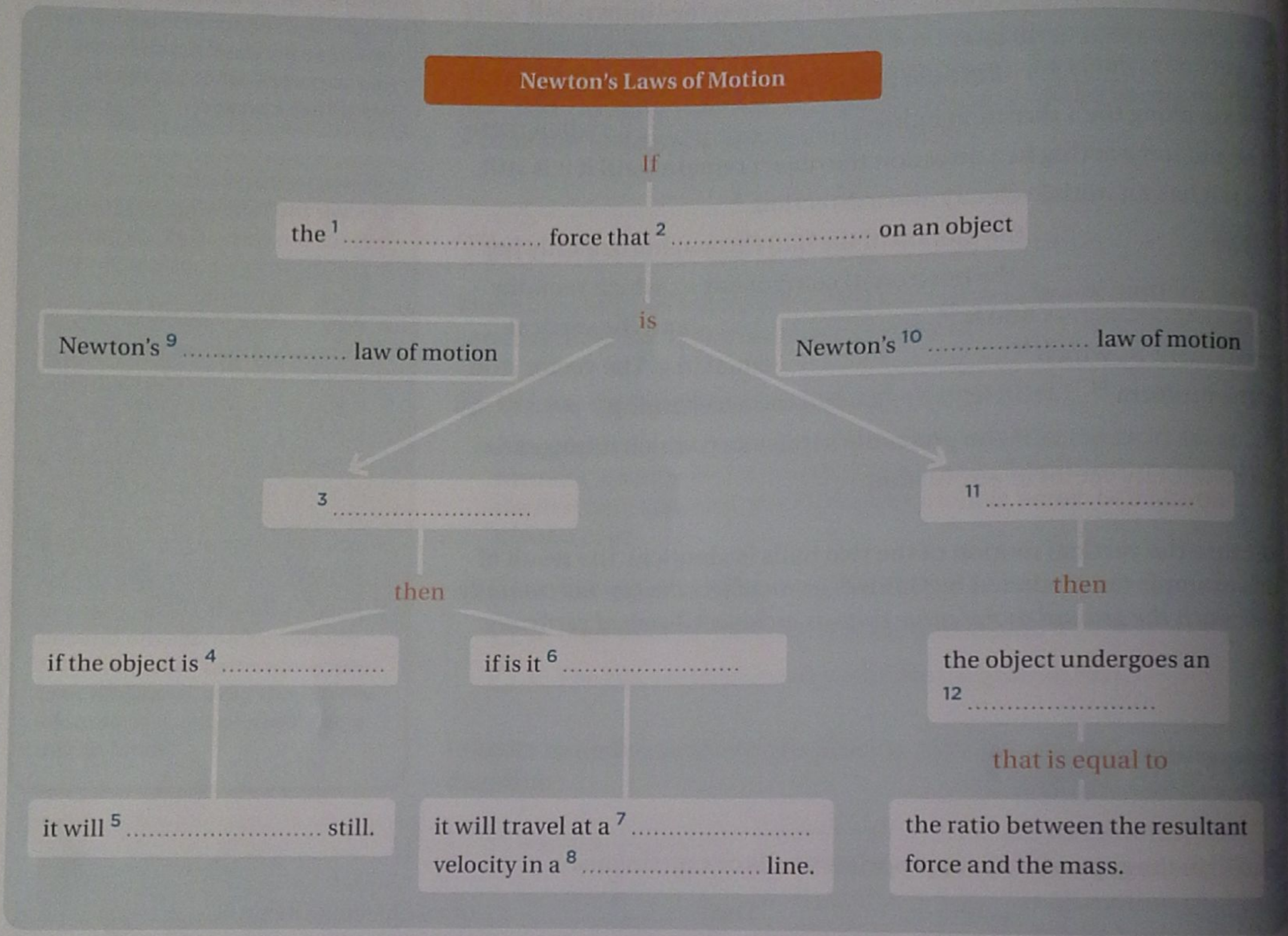
The [1] .... of an object is always [2] .... the ratio between the [3] .... force and the object's [4] .... Its acceleration is a [5] ...., the direction of [6] .... is always equal to the [7] .... of the resultant vector. Finally its acceleration remains [8] .... or varies, depending on [9] .... the resultant is constant or [10] ....

5 The bold words below are in the wrong sentences, so the sentences don't make sense at all! Using "Introduction" and "Expressing Newton's Second Law" to help you, put the bold words in the right sentences.

1 Newton's second law of motion **causes** with nonzero net forces.
2 A nonzero net force makes an object **accelerates** an acceleration.
3 The harder you throw something, the faster it **decrease**.
4 A nonzero net force **acts** acceleration.
5 Friction causes the velocity of an object to **undergo**.
6 Friction **deals** against the direction of motion.

6 **Fill in the gaps in the diagram with the appropriate words.**

resultant	remain	moving	first
still	nonzero	straight	second
zero	constant	acceleration	acts



7 **There are four statements after the following sentences. Which is correct? Explain why, and use the texts in this unit to help you.**

1 **A man is skiing down a hill at a constant speed.**
   a The effect of friction caused by the ice cannot be ignored.
   b No forces are being applied to him.
   c It is possible that only a single force is acting on the skier.
   d The frictional force is lower than the gravitational force.

2 **You hit an object, which experiences a net force and accelerates.**
   a The acceleration has the same direction as the object's velocity.
   b The object moves in the direction of the net force.
   c The object moves in the opposite direction to the net force.
   d The object's acceleration has the same direction as the net force.

3 **A car travelling westward suddenly begins to slow down.**
   a The braking force is directed westward but its intensity is decreasing.
   b The net braking force is directed eastward.
   c The braking force is directed westward and its intensity is increasing.
   d The net resultant force is directed westward.