Physics Factsheet

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Newton's Laws and Circular Motion

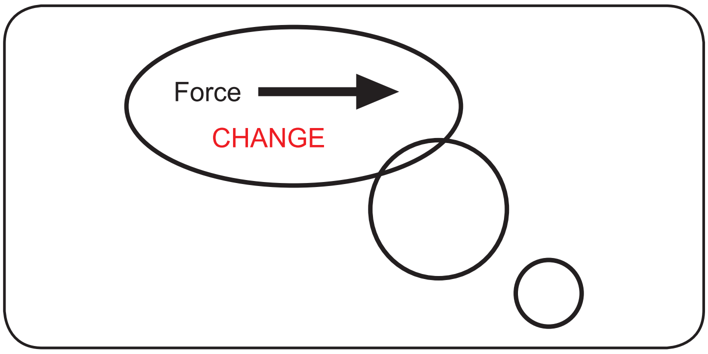
Most GCSE students are able to quote Newton's Laws, but many mistakes made in answers to A Level questions show a lack of knowledge of the implications of them.

This Factsheet aims to clarify the understanding of Newton's Laws and concepts of circular motion to give you a really good grounding for your A Level Course.

Forces cause change

1) Many students associate force with movement, but this can be misleading. An object can be moving even if there are no forces acting on it, or if the resultant force is zero. In fact, if an object is moving at constant velocity, then the resultant force **must be zero**. It is much more helpful to associate force with **change**. Try to fix it in your thoughts that **forces** cause **change**.

Figure 1



2) Forces cause change:
   a) If an object is stationary, an unbalanced force will start it moving.
   b) If an object is moving, an unbalanced force in the direction of motion will cause it to accelerate (speed up) or decelerate (slow down).
   c) If the force is at an angle to the direction of movement, it will cause it to change direction.
   d) In some circumstances a force can cause the object to change shape (we shall not concern ourselves with change of shape in this Factsheet).

Speed, Velocity and Acceleration

You will be familiar with the concept of **speed**, as rate of change of position – the distance travelled in one second, with the unit of ms^{-1}, but as you start your A Level course it is important to be more careful how you use language (see the Factsheet "How to avoid losing marks – language" for common examples).

Some students confuse **speed** and **velocity**. Velocity has the same numerical value and the same units as speed, but the **direction** matters too. Thus, an object can be moving at steady speed, but if it is changing direction, then its **velocity** is changing.

> ***Key Points:***
> *1) Forces cause change.*
> *2) The Specifications require correct use of technical language and will penalize incorrect use.*

Remember force, acceleration and velocity are all **vector** quantities. The direction matters as well as the size.

Circular motion, which will be dealt with later in this Factsheet, is an example of constant **speed**, but changing **velocity** caused by a force acting at right angles to the direction of motion.

Acceleration is **increase in velocity in one second**. Since the units of velocity are ms^{-1}, the units of acceleration must be **ms^{-1} per s i.e. ms^{-2}**.

Newton's Laws

Newton's 1st Law expresses the idea that has just been put forward, that if there are no forces acting on an object or the resultant force is zero, then either it is stationary, or if it was already moving, then it will carry on at the same speed in a straight line.

Newton's 2nd Law tells us what happens when there **is** an unbalanced force acting on an object. It depends what the object is doing when the force is applied.

If the object is stationary then it will begin to move.

If it is moving and the force is in the same direction as the motion, then, it will accelerate.

If it is moving and the force is in the opposite direction to the motion, then it will decelerate.

> ***Key Points:***
> *1) If an object is travelling at steady speed in a straight line, the resultant force on it must be zero.*
> *2) If the resultant force on an object is zero, it is either stationary, or moving at steady speed in a straight line.*

> ***Exam Hint:*** *Try to be more precise than just "move". Do you mean "move at steady speed", "accelerate" or "decelerate"?*

Some students, even if they have quoted Newton's 1st Law correctly, go on to answer questions thinking that a force is still necessary to keep an object moving. Presumably this is because they are allowing a superficial acquaintance from everyday life to override their understanding of Newton's ideas. In everyday life if an object has been caused to start moving, it often does then slow down and stop after it has been released, but this is not because it needs a force to keep it moving, it is because there are nearly always forces such as air resistance and friction acting in the opposite direction to the motion to cause the object to decelerate.

You will no doubt be familiar with the formula expressing Newton's 2nd Law.

Key Point: F = m x a

F → Force/N; m → mass/kg; a → acceleration/ms^{-2}

This just tells us how much acceleration we get for a given force on a given mass.

Worked examples:

1) *A shopper is pushing a supermarket trolley of mass 12kg, at steady speed, by applying a fore of 10N. When he gets tired, his push reduces to 6N. Assume air resistance is negligible.*
   a) *What is the total resistive force on the trolley?*
   b) *What is the deceleration of the trolley when the shopper reduces his force?*

Answer:

   a) *The total resistive force must be 10N because the trolley is moving at steady speed.*
   b) *When the push is only 6N, the resultant force is -4N, so the deceleration*
   *= 4N/12kg = 0.33*ms^{-2}

2) *When a car travelling at 12.5* ms^{-1} *brakes suddenly, the passenger's speed is reduced to zero by the airbag in 1.5s. If he has a mass of 80kg, what is the average force on the passenger?*

Answer:

*Deceleration = (12.5 – 0) /1.5 = 8.3*ms^{-2}*, so force = 80 x 8.3 = 664N*

Test your understanding:

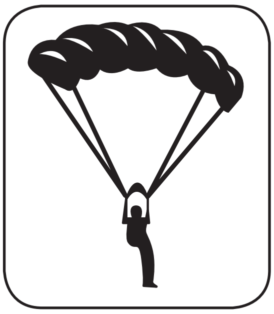
1) *A parachutist with a mass of 60kg jumps from an aeroplane. At the instant when she leaves the plane the only force acting on her is her weight.*
   a) *What is her weight?*
   b) *What is her initial acceleration?*

   As she accelerates, air resistance increases.
   At a certain point the air resistance on her is 400N.
   c) *What is the resultant force acting on her at this instant?*
   d) *What is her acceleration at this point?*

   Before she opens her parachute, she reaches terminal velocity.
   e) *What will the value of the air resistance be when she is travelling at terminal velocity?*

   When she opens her parachute, the air resistance increases almost instantaneously to 800N.
   f) *What is the resultant force acting on her now?*
   g) *What deceleration will this cause?*

Figure 2



Test your understanding:

2) *A rocket has a mass of 1.25 x* 10^6*kg. Throughout this question neglect air resistance and the decrease in weight of the rocket due to burning off fuel.*
   a) *What is its weight?*

   It is launched with a thrust of 3.6 x 10^7*N. This thrust continues after the rocket leaves the launch pad.*
   b) *What is the net force on the rocket?*
   c) *What acceleration will this force produce?*

   As the rocket gets further away from the earth, the earth's gravitational field is less strong.
   d) *At a point where the pull is only 1/5 of that at the earth's surface, what will be the weight of the rocket?*

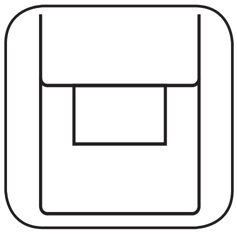
   At this point, the rocket motors burn out and the thrust from them ceases.
   e) *What is the net force on the rocket now?*
   f) *What effect will this force have on the rocket's motion?*

Exam Hint: *Do not be deceived into thinking that the parachutist suddenly accelerates upwards when she opens the parachute, as it often looks in films on TV. She continues moving downwards, but decelerates. The effect that you see is because the cameraman/woman has not decelerated, so s/he is continuing downwards at a greater rate than the parachutist.*

Test your understanding:

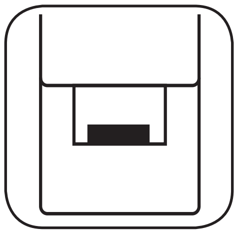
3) a) *A sealed wooden box is just floating in water. Its weight acts downwards and the upthrust of the water (given by the weight of the water displaced) acts upwards. What can you say about the 2 forces?*

Figure 3



   b) *The box is removed, a weight is added and it is resealed. Explain what will happen to the box now and why.*

Figure 4



A Level Interpretation of Newton's Second Law

For your A Level studies you will be expected to see that the version of Newton's 2nd Law given above is a special case where the mass remains constant and the velocity changes – this is a normal situation, but there are cases where the mass or both mass and velocity change. The A Level expression of Newton's 2nd Law is: "**Force equals rate of change of momentum**".

Key Points:

1) Force equals rate of change of momentum = rate of change of (M x V)

Mass/kg Velocity/ms^{-1}

For constant M this reduces to mass x acceleration, but if mass changes and V remains constant it is V x rate of change of M

If both M and V change it is (M x rate of change of V) + (V x rate of change of M).

Test your understanding:

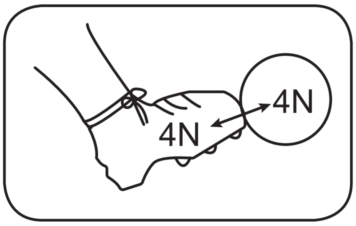
4) a) Try to think of an example where the velocity stays the same, but the mass changes.

b) Try to think of an example where both mass and velocity change.

Newton's 3rd Law is usually quoted as "Action and Reaction are equal and opposite". Again, most students can quote this law, but make mistakes when applying it. It is important to get a good grasp of the basic idea for the A Level work to come.

Whenever two objects interact, each exerts a force on the other, which is equal in size and opposite in direction. E.g. If I kick a football with a force of 4N, the ball exerts a force of 4N back on my foot.

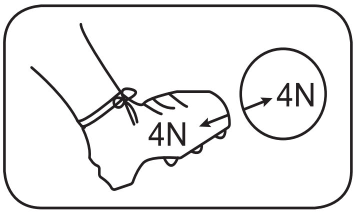
Figure 5



A difficulty in drawing diagrams like these is that the forces act **only** while the two objects are in contact, but then it is not easy to see that one of the forces acts on the **ball**, while the other acts on the **foot**.

It is clearer if the two objects are separated, but then it looks as if the forces continue after the contact is broken.

Figure 6



During the brief time of contact, the ball experiences a force of 4N, which gives it a rapid acceleration, so that it leaves the foot with a certain velocity. After the contact, there is no longer a force acting on the ball from the foot.

The force acting on the foot during the contact could either give it an acceleration in the opposite direction or be absorbed by the boot and bones of the foot.

Diagrams in which the objects are separated for clarity, even though they are in contact are often called "Free-Body Force" diagrams.

Test your understanding:

5) A high-jumper takes a run-up and then pushes into the ground to take off for the jump.
What force pushes the jumper into the air?

6) A gun fires a bullet forwards with a force of 10N.

a) What force acts on the gun?

b) What effect might this force have on the gun?

Newton's Pairs of Forces

For A Level you may be asked to identify "Newton's Pairs" of forces, and a clear understanding of the forces and reaction forces is necessary to avoid mistakes.

To help you identify Newton's Pairs they must be:

1) Of the same type (gravitational, magnetic, contact etc.)
2) Of the same magnitude.
3) Acting in opposite directions.
4) Acting on different objects.

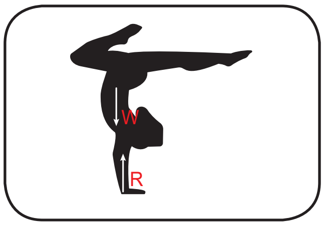
Test your understanding:

7) The diagram shows a gymnast on the balance beam, and the free-body force diagram.

*a) Explain why the forces shown on the free-body force diagram are **not a Newton's Pair**.*

Figure 7

Figure 8



Source: https://www.appliquesquiltsandmore.com/

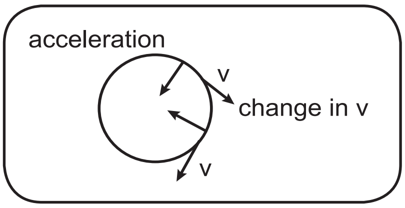
b) What is the other force of the Newton's Pair to the gymnast's weight?

Circular Motion

Newton's 1st Law tells us that if the resultant force on an object is zero, then it will carry on in the same straight line at steady speed. So, if an object is going around in a circle, there must be a resultant force on it. In order to go around in a circle, an object must have something to provide the necessary force. This necessary force is called "**Centripetal Force**", but it is important to understand that centripetal force does not exist as an entity, it is the force which must be provided by some agency, in order for the object to travel in a circle.

Newton's 2nd Law implies that if there is a force there must be an **acceleration**, so it would seem impossible for an object to travel at steady speed in a circle, until you think about the reminder you were given earlier that **force**, **acceleration** and **velocity** are vector quantities. The object travels at steady **speed**, but its **velocity** is changing because the **direction** is changing. This **change in velocity** constitutes an **acceleration**, which is always **towards the centre of the circle**.

Figure 9



For GCSE you do not have to know how to calculate the size of the centripetal force, but you should know that it:

- Increases with increase in the mass of the object
- Increases with increase of the speed of the object
- Decreases with increase in radius of the circle.

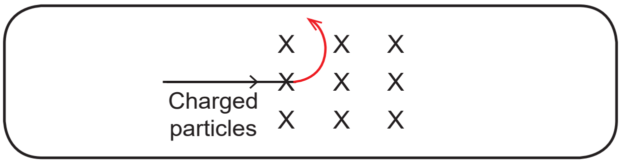
Key Points:
1) Centripetal force is the force necessary to constrain an object to move in a circle.
2) For A Level, you will be expected to know and use the formula for the necessary centripetal force mv^2/r, where m is the mass, v the velocity, and r the radius.

Worked example:
2) A planet maintains an orbit around a star at steady speed in a circle.
   a) What force provides the necessary centripetal force?
   b) What would happen to the planet is this force suddenly ceased?

Answer:
   a) Gravitational attraction.
   b) The planet would fly off at a tangent and continue in a straight line at constant speed.

Test your understanding:
8) A child is whirling a stone on a string, so that it moves in a horizontal circle at steady speed.
   a) What force provides the centripetal force for circular motion?
   b) How can the stone be said to be accelerating, if it is travelling at steady speed?
   c) In which direction is the acceleration?
   d) Describe the motion of the stone if the string breaks.
9) A washing machine gets rid of water in the drying phase, by whirling round at high speed.
   a) What force provides the centripetal force for the circular motion of the clothes in the drum?
   b) Why does the water fly out of the holes in the drum?
10) Charged particles travelling a steady speed v, enter a magnetic field, whose field-lines are into the plane of the paper, as shown in the diagram.

Figure 10



They follow the track shown.
a) How can you tell from the diagram that the magnetic force on the particles is at right angles to the direction of travel of the particles?
b) Given that the magnetic force = Bqv, where B is the field strength, q the charge on the particle and v the velocity, equate the magnetic force on the particles to the necessary centripetal force and transpose it to give an expression for r the radius of the circle.

Answers for "Test your understanding":
1) a) Her weight is 600N (for GCSE you have used 'g' as $10Nkg^{-1}$; for A Level, you will be required to use the more precise 9.81).
   b) F = ma, so a = F/m = $10ms^{-2}$
   c) Resultant force = 600 – 400 = 200N
   d) F = ma, so a = F/m = 200/60 = $3.33ms^{-2}$
   e) Resultant force = 800 - 600 = 200N upwards
   f) Deceleration = F/m = 200/60 = $3.33ms^{-2}$
   g) When she is travelling at terminal velocity the air resistance will be 600N.
2) a) Weight = $1.25 \times 10^6 \times 10 = 1.25 \times 10^7$N
   b) Resultant force = $3.6 \times 10^7 - 1.25 \times 10^7 = 1.35 \times 10^7$N
   c) Acceleration = F/m = $1.35 \times 10^7 / 1.25 \times 10^6 = 10.8ms^{-2}$
   d) Weight of rocket = $1.25 \times 10^7 /5 = 0.25 \times 10^7$N
   e) The net force is its weight 2.5×10^6 N
   f) This force will cause the rocket to decelerate.
3) a) The 2 forces are equal in size and opposite in direction.
   b) The box will accelerate downwards until it reaches the bottom, because the upthrust is still the same, but the weight has increased, so there is an unbalanced force downwards.
4) a) Sand being poured onto a belt moving at steady speed.
   b) A rocket moving in a decreasing gravitation field, using up fuel.
5) The contact force from the ground pushes her up into the air.
6) a) The force on the gun is 10N backwards.
   b) If the gun is free to move it will accelerate in the opposite direction or it will deform.
7) a) The forces are not a Newton's pair because i) they are different types of force (gravitational attraction and contact force) ii) they are acting on the same object.
   b) The gravitational attraction exerted by the gymnast on the Earth is the other one.
8) a) The tension in the string provides the necessary centripetal force.
   b) The stone is accelerating because its direction (and therefore velocity) is changing.
   c) The acceleration is towards the centre of the circle.
   d) The stone would fly off at a tangent and continue in a straight line at steady speed (neglecting air resistance.) because there is no longer anything to provide the necessary centripetal force.
9) a) The reaction of the drum against the clothes provides the centripetal force.
   b) At the holes in the drum, there is no surface to provide the reaction, so nothing to provide centripetal force and the water continues through the holes at steady speed in a straight line.
10) a) The track is circular.
   b) $mv^2 /r = Bqv$ So $mv/Bq = r$

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