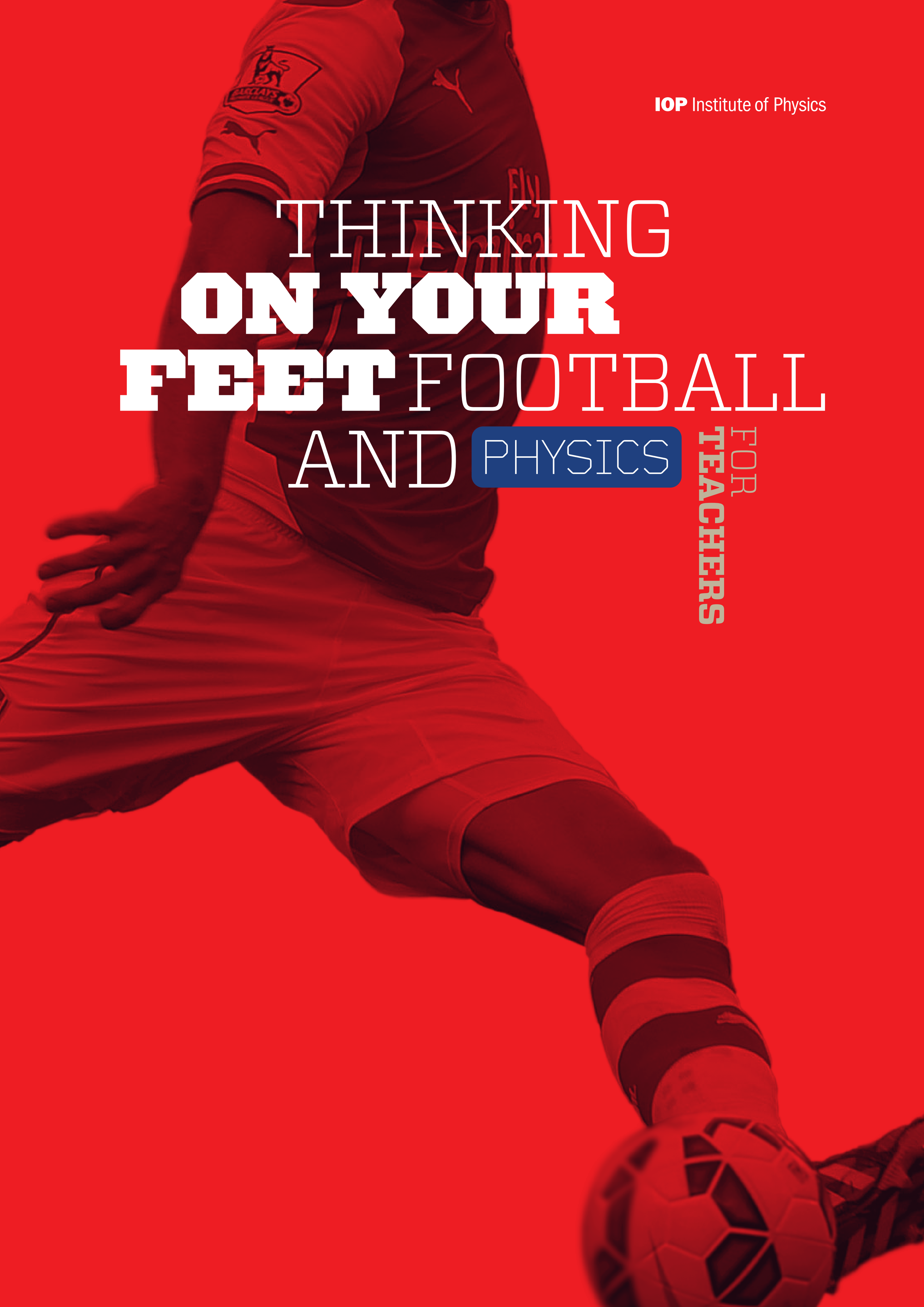
IOP Institute of Physics

THINKING ON YOUR FEET FOOTBALL AND PHYSICS

FOR TEACHERS



The Institute of Physics is a leading scientific society. We are a charitable organisation with a worldwide membership of more than 50,000, working together to advance physics education, research and application. We engage with policymakers and the general public to develop awareness and understanding of the value of physics and, through IOP Publishing, we are world leaders in professional scientific communications.

In September 2013, we launched our first fundraising campaign. Our campaign, Opportunity Physics, offers you the chance to support the work that we do.
Visit us at www.iop.org/fundraising

Acknowledgements

This resource was written by Lawrence Cattermole and Neil Atkin.

Thanks to Jack McNicholl and Samir Singh from Arsenal in the Community for supporting the development of this resource.

Designed and produced by chacha.co.uk

CONTENTS

INTRODUCTION

Thinking on your feet: football and physics is a pack of resources aimed at engaging students with physics by showing its relevance to football. The pack is structured into eight sessions intended to be organised as extra-curricular activities. Each session, like a football match, consists of '45 minutes each way' with the first half being done in the classroom exploring the physics, and the second half on the pitch applying the ideas.

The resources are intended for students aged 11-16. While being designed to be accessible to younger students, they can also provide suitable challenges to stretch higher-attaining pupils. The approach has proved popular and successful with both boys and girls, and it is hoped that the resources have the potential to widen participation in physics by engaging with hard-to-reach students.

WHAT DO STUDENTS DO IN THE SESSIONS?

Each session starts in the classroom with a teacher introduction that poses a question of key importance in football, relating to different areas of an expert footballer's performance. The focus is then narrowed to show how a specific aspect of physics can be used to give an insight into why footballers do what they do.

Students then move on to the main activity in which they try to design a practical demonstration that could be used to support an explanation of the physics underlying this aspect of footballing performance. The emphasis, therefore, is on thinking about how they can explain the ideas to an audience (e.g. of their friends, or football fans), rather than on doing a traditional investigation to find an answer. Students are encouraged throughout the materials to think creatively about how to communicate the ideas, including using their mobile phones, where available, to make video clips of the practical demonstrations. The most important thing is that every student should have a positive experience and feel that there is something that physics has to say about football, even if they are not able to fully articulate a complete explanation.

These ideas can then be explored further by applying them on the pitch. As well as focusing on improving their own footballing performance, students need to test out the ideas that they developed in the practical demonstrations and see how they apply in the richer context of football. After the session there are further practice activities that students can undertake in their own time to improve their skills and their understanding of the physics.

OVERVIEW OF SESSIONS

SESSION	TITLE	KEY PHYSICS IDEAS	IN THE CLASSROOM STUDENTS SHOULD:	ON THE PITCH STUDENTS SHOULD PRACTISE:
1	How can you kick and throw a ball further?	Projectiles Velocity, distance, angle Experimental design	Make predictions about what angle might give the largest range based on thinking about extreme conditions. Plan an experiment to find the optimum angle to kick or throw a ball. Draw conclusions from their results and evaluate the method used. Relate what they have learned to the real world and why measured values may not match the theoretical value.	Throwing and kicking the ball at different angles to find the optimum angle for increasing the range. Techniques that enable them to kick and throw at this angle. Improving the distance they can manage to throw and kick.
2	Taking better penalties	Accuracy, probability Experimental design	Make predictions about the best place to aim for penalty kicks. Observe videos of penalties and record their observations. Analyse data about the outcomes of penalties. Draw conclusions from data and use these to suggest successful strategies for penalty takers and goalkeepers. Calculate time of travel of a ball from given data.	Improving their penalty kick technique. Disguising which way they will kick the penalty. Choosing a suitable spot in the goal and being able to hit that target.
3	How can you accelerate faster?	Distance, displacement, speed, velocity, acceleration	Use appropriate terminology to describe the motions of objects. Distinguish between speed (or velocity) and acceleration. Investigate and measure the motion of a rolling marble. Design a demonstration to show the difference between acceleration and top speed.	Running on their toes and running with the ball under control. Explosive starts and improving their acceleration. Knowing how to get ahead of an opponent who has a greater acceleration. Beating the offside trap in a free kick.

OVERVIEW OF SESSIONS

SESSION	TITLE	KEY PHYSICS IDEAS	IN THE CLASSROOM STUDENTS SHOULD:	ON THE PITCH STUDENTS SHOULD PRACTISE:
4	What makes a good pass?	Effects of forces Friction and air resistance Force diagrams	Use modeling to demonstrate the relative times it takes for a ball to arrive at a teammate's feet, depending on the type of pass. Identify the forces acting on an object as it moves along the ground or in the air. Draw and label force diagrams using conventions presented. Relate the practical demonstration to the way that footballers pass the ball.	Passing a ball accurately on the ground over greater distances. Establish over what distance each player needs to loft the ball to get the distance.
5	Forceful tackling	Force, impact area, stress	Recognise that certain factors increase the risk of injury from tackling. Design a practical demonstration that shows these effects, qualitatively and quantitatively. Explain how a reduced impact area increases the potential damage done. Relate the practical demonstration to safe and dangerous play.	Taking each other on, trying to get past with the ball. Jockeying an opponent to prevent them getting past with the ball. (With appropriate coaches/ teachers only: safe ways of tackling.)
6	How can you control a ball effectively?	Elastic and inelastic collisions, energy Materials, structures	Recognise that different parts of the body can be used to control a moving ball, either to stop it or redirect it. Explain how controlling the ball depends on the part of the body used and how much the ball is actively cushioned. Design a demonstration that shows how much a ball rebounds from different surfaces and structures. Relate the demonstration to the way that footballers control the ball.	Controlling the ball with different parts of the body, including softer parts e.g. chest and thigh. Actively 'cushioning' the ball with different parts of the body. Safely heading the ball.

OVERVIEW OF SESSIONS

SESSION	TITLE	KEY PHYSICS IDEAS	IN THE CLASSROOM STUDENTS SHOULD:	ON THE PITCH STUDENTS SHOULD PRACTISE:
7	Using your body for balance and stability	Centre of mass Balance and stability	Recognise that the stability of objects is dependent on several factors, including how the mass is distributed within the object. Design a practical demonstration that shows this effect. Identify the differences in effect between an inanimate object and an active person in balancing. Relate the practical demonstration to the way that footballers move in different situations.	Changing direction quickly, with and without the ball. Paying more attention to body movements when practising any skill. Trying to repeat any movement performed with its mirror image.
8	How can you spin and bend the ball?	Translational and rotational motion Backspin, topspin, sidespin Surface contact, effect of air	Recognise that spherical or cylindrical objects can be made to spin and this affects their movement through the air. Design a demonstration that shows these effects using video. Explain how spin can be imparted on a spherical or cylindrical object and why it affects the motion. Relate the demonstration to the way that footballers spin and bend the ball in different situations.	Different ways of kicking across the ball to get spin. Exploring sidespin with the inside and outside of the foot. Exploring backspin and topspin and trying to kick it with no spin.

WHAT IDEAS ARE COVERED IN THE SESSIONS?

From a footballing perspective, the early sessions (1-3) are intended to motivate through their focus on maximizing performance on simple tasks (distance of kick, accuracy, running speed). Sessions 4-6 look at basic aspects of the game (passing, tackling, controlling the ball), while sessions 7-8 are concerned with more subtle aspects of the game (balancing the body, bending the ball).

There is a similar progression in the physics ideas, starting with basic experimental design and measurements, and then dealing with physics concepts such as velocity and acceleration, forces, energy, centre of mass, and translational and rotational motion.

There are broader and more fundamental physics ideas that run throughout the approach.

A key idea is that of **modelling –** the football context is complex, but each of the practical activities uses simple equipment to model one particular aspect of the real situation which is of interest. For example, depending on the behaviour being investigated, a football can be modelled with a beanbag, a blow ball or a pair of plastic cups.

Another key idea is that physics is nothing without **measurement –** carrying out repeated readings and paying attention to precision can be critical in the context of football in order to identify patterns from the noise of the data.

An important aspect of the **explanations** that students need to construct is being able to reason with relationships – how one factor is related to another, what happens when limits are approached, and how to deal with factors whose effects work in opposite directions.

Although there is a progression in both football and physics aspects in the sequence of sessions, they can be used independently of each other and they could be done in any order. Later sessions tend to be more demanding than earlier ones, though any of the sessions could be adapted to make them simpler or more challenging, depending on what will be accessible and appealing to students.

HEALTH AND SAFETY

For each activity, safety advice is given to help you assess any risks. In drawing it up, we have assumed an average group of 11 to 14 year-olds. You may need additional control measures if working with younger pupils, those with behaviour problems or pupils with motor control difficulties. You should do your own risk assessment for each activity.

WHAT IS IN THE PACK OF RESOURCES?

Thinking on your feet: football and physics consists of a Teachers' Handbook (this publication) and a separate Coaching Manual, with additional resources downloadable from the website **iop.org/football**

The Teachers' Handbook is in two parts. In the first part, each session includes a narrative that outlines the footballing context, how the ideas can be explored experimentally and a physics story that provides the explanation, along with brief guidance notes on how to organise the activities in the classroom. The second section provides more detailed background about the physics, which may be particularly helpful for non-specialist teachers.

The Coaching Manual is also in two parts. The first part includes brief guidance notes on how to organise the activities on the pitch, with further background information in the second part. Since the activities on the pitch may be run by a non-specialist science teacher (a PE teacher or a coach, for example), the guidance notes include a brief summary of the key physics ideas covered in the classroom session so that the links can be made.

WHAT IS ON THE WEBSITE?

The website has PowerPoint presentations for the teacher to use in the classroom sessions, and sheets for the students to use in the classroom (physics activity sheets) and on the pitch (football record sheets). It also contains PDFs of the Teachers' Handbook and the Coaching Manual.

Some teachers may prefer to keep the sessions more informal, and to base the activities just on the PowerPoint presentations and class discussion; others may prefer the structure provided by the student sheets. The 'physics activity sheets' may also be useful to those teachers who wish to adapt the sessions for use in science lessons as part of the curriculum.

SESSION 1

HOW CAN YOU KICK AND THROW A BALL FURTHER?

Footballers often need to kick or throw a ball as far as possible, for example, when clearing the ball from defence or for an attacking throw-in.

In addition to how hard it is kicked or thrown, the distance the ball travels depends on its launch angle. For an ideal projectile, the optimum theoretical angle is 45°, but in the real world there are other factors to take into account.

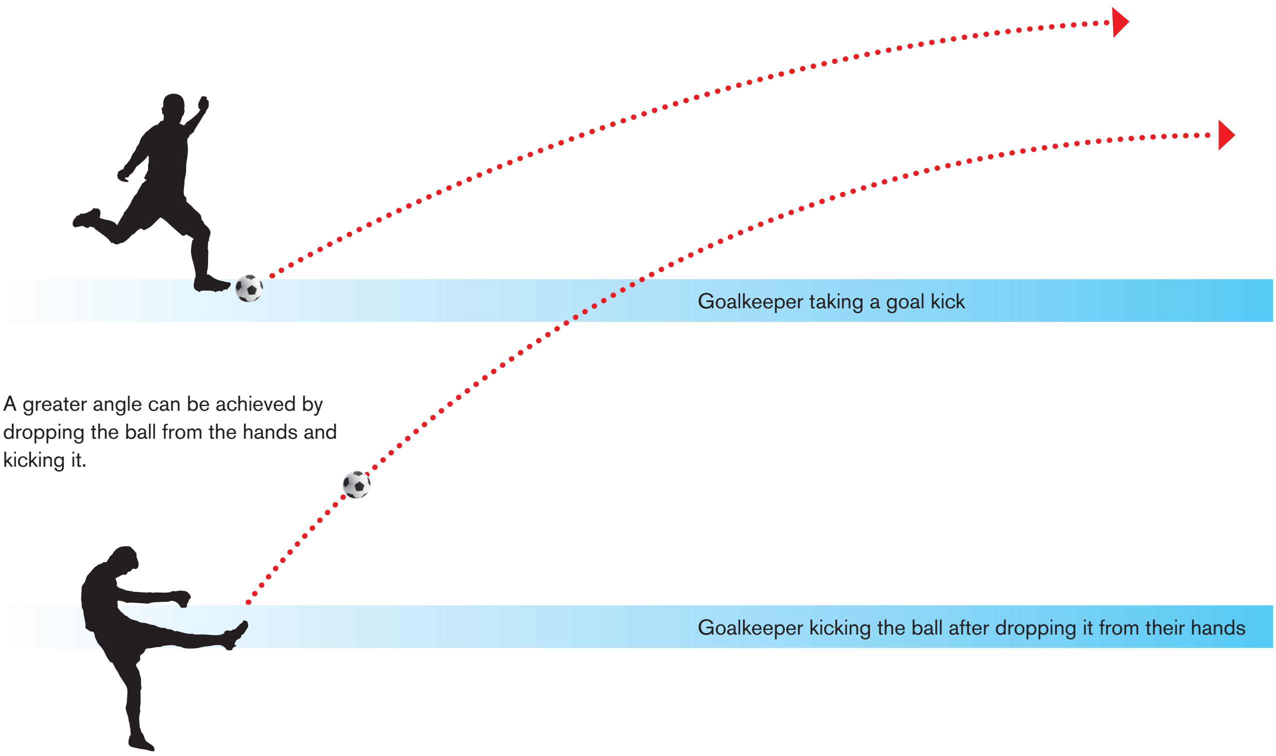
FOOTBALLERS IN ACTION

How hard the ball is kicked or thrown obviously affects how far it travels. Footballers practise their technique and strength to increase the velocity of their kicks and throw-ins to make the ball go faster and further. The angle also affects how far it travels, and particularly for throw-ins, it is possible to increase the distance simply by altering the angle, with no other changes to technique.

Goalkeepers are particularly good at kicking a static ball long distances from the ground since they need to do this for goal kicks. It is a difficult technique to master, as can be seen regularly in junior football where the opposing team closes in on a goalkeeper with a weak goal kick. It is possible for a goalkeeper to get a better angle and kick it much further by dropping it from their hands. Similarly defenders sometimes flick a ball up with their foot before they 'hoof' it upfield.

When a goalkeeper takes a goal kick, the ball is kicked from the ground at a relatively low angle.

A greater angle can be achieved by dropping the ball from the hands and kicking it.



EXPLORING THE IDEAS EXPERIMENTALLY

There are a number of factors that influence the distance that a ball travels when it is kicked or thrown. This session focuses on how to choose the best angle to make the ball go as far as possible (i.e. to maximize the range). To model the trajectory of a football, a convenient method is to use 'blow balls'. Packs are readily available from party suppliers, and consist of a set of balls and a blowpipe.

Before students start to use the equipment they should be asked what they think might be the optimum angle. They also need to consider a number of aspects of experimental design, such as the factors they need to keep constant (how hard they blow, using the same blowpipe and ball, the same person blowing and measuring), and where the ball should be launched from (as close to the bench or the floor as possible).

Although there is a great deal that could be done here on ideas about measurement, within the timescale of this session the emphasis should be on exploring the phenomenon, without focusing too much on repeatability, precision and accuracy.

When a ball is launched two factors affect how far it travels: how fast it is launched and what angle it is launched at. In this case we are only looking at what effect the angle has on the range, so the students need to try and blow as consistently as possible each time.

TELLING A PHYSICS STORY

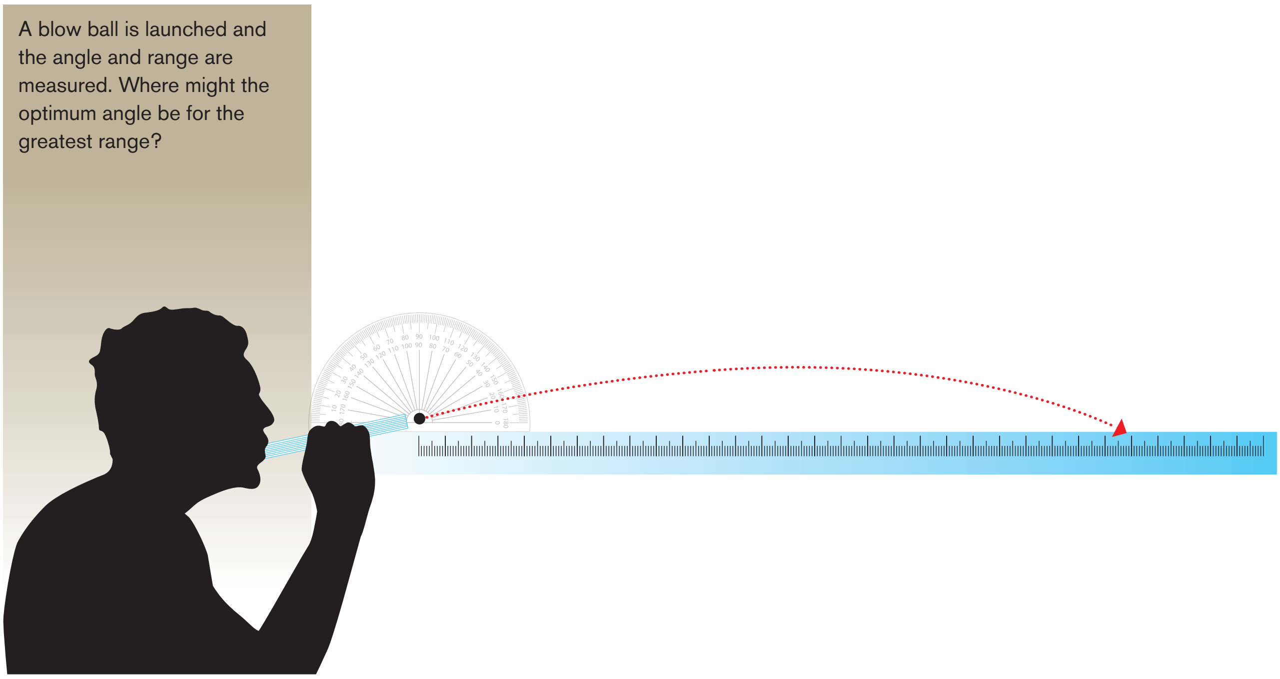
A preliminary exploration using this equipment will show that very steep angles and very shallow angles of launch are not effective for making the ball travel a long distance. More systematic measurements over a range of angles will in fact reveal that the optimum angle for the blow ball is around 40°.

One reason the optimum angle for a football is not 45° (the theoretical value) is that this does not take air resistance into account. The effect of the air is to decrease the angle. There are a number of other factors that affect the optimum launch angle – the effects of headwinds or backwinds, the angle that allows the player to exert most force on the ball, and the effects of spin on the ball.

Although the theoretical value for an ideal projectile is 45°, reality is more complex. It is not easy to say what the optimum value would be for a football, because it will depend so much on the context of the particular kick or throw in the real world.

USING THE IDEAS ON THE PITCH

Students will be practising techniques for throwing or kicking the ball as far as possible, and will be exploring the effects of angle on the range of the ball.



A blow ball is launched and the angle and range are measured. Where might the optimum angle be for the greatest range?

CLASSROOM GUIDANCE

OBJECTIVES

Students should:

- Make predictions about what angle might give the largest range based on thinking about extreme conditions.
- Plan an experiment to find the optimum angle to kick or throw a ball.
- Draw conclusions from their results and evaluate the method used.
- Relate what they have learned to the real world and why measured values may not match the theoretical value.

RESOURCES

For each group:

- Blow tubes and blow balls (available from party suppliers: ensure that safety tubes are used – these prevent the blower from sucking the ball into the mouth)
- Metre rule, semi-circular protractor, string, cardboard, paper, pencils
- Safety glasses
- Access to disinfectant solution
- Desk fan (optional)
- Students' mobile phones with video function (optional)

SUGGESTED STRUCTURE AND TIMINGS

5 mins — Introduce how footballers can kick and throw the ball a long way.

10 mins — Discuss the ideas and how they might find the optimum angle.

20 mins — Organise students into groups to design and carry out their investigation.

10 mins — Bring the whole class together to share their ideas and relate to what footballers do.

TEACHING POINTS

CAUTION: Ensure good hygiene. Ideally, have sufficient blowpipes for one per student. After the session, these should be placed in a basin of disinfectant solution. If students are sharing blowpipes, they should dip the end in disinfectant solution and rinse before use. Minimise problems of balls hitting other students by organising the positions of the groups appropriately.

In the class discussion at the start, students should understand that the angle and the speed of the ball affect the range. Working in pairs they should write down what they think will be the optimum angle and why. After considering extreme examples of the ball kicked at 90° and 1° , they could conclude that an intermediate angle around 45° might give the optimum range.

They could then carry out some rough trials with the equipment, before another class discussion gets them to focus on identifying variables to change and those to control. They can then plan how to get some readings and carry out the experiment.

An alternative to the blow tubes/balls is to use paper tubes made by wrapping a piece of paper around a drinking straw and taping the end. The paper tube can be launched by blowing down the drinking straw.

If students have time they can simulate a headwind or backwind by positioning a desk fan in front of them or behind them, to see if they can determine how this may affect the angle.

It will be quite difficult for students to get accurate results within the short time and basic equipment used, but there are opportunities in discussion to include ideas such as accuracy, variable, range of value, repeated readings, measurement uncertainty, and so on.

ON THE PITCH

These ideas will be relevant when students practise the following on the pitch:

- Throwing and kicking the ball at different angles to find the optimum angle for increasing the range.
- Techniques that enable them to kick and throw at this angle.
- Improving the distance they can manage a throw and kick.

SESSION 2

TAKING BETTER PENALTIES

Penalties, and particularly penalty shootouts, are highly charged affairs, and are responsible for determining the outcome of many matches. A penalty is a psychological as well as physical duel between a goalkeeper and the penalty-taker.

To some extent, luck is involved. Just as in any game of chance, it is very useful to understand the probabilities of success for different actions. Knowing which shots are most likely to score could give a team a critical edge in a match.

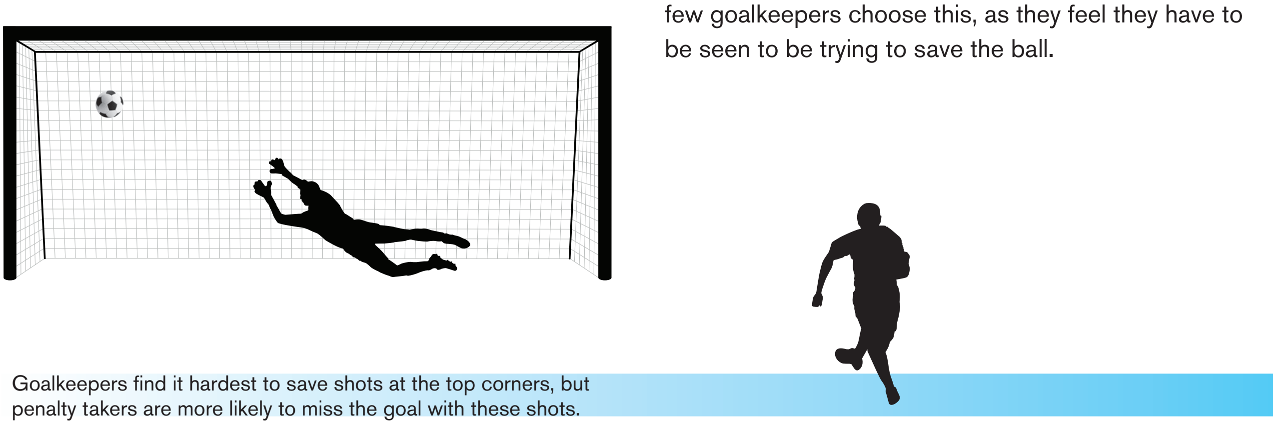
FOOTBALLERS IN ACTION

The penalty kick is one of the highest pressure situations in any sport, particularly in the penalty shootouts that decide games in cup competitions. Goalkeepers analyse videos of penalty-takers (and vice versa) to see if they have a preference. The chances of a goalkeeper second guessing correctly however are not high. A study of all the penalty shots in World Cup Finals games between 1982 and 1994 found that they make the correct decision only 41% of the time and save only 14.5% of shots. The advantage is with the penalty-taker.

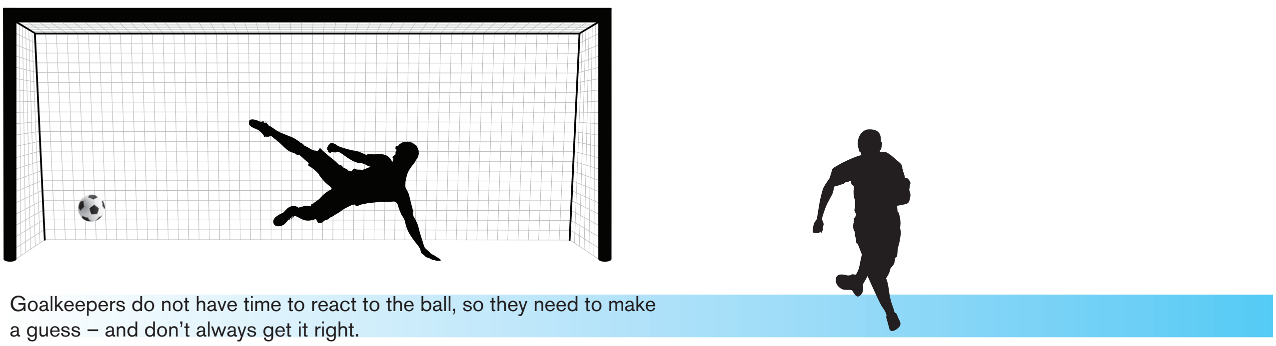
It does not take long for a ball kicked hard from the penalty spot to arrive at one of the corners of the goal. Goalkeepers do not have time to wait and react to the direction of the ball so they have to make a decision before the ball is actually kicked.

The penalty taker also needs to make a decision before kicking the ball – where to aim it. The hardest penalty for a goalkeeper to save is a fast shot in either top corner, but this is also the area where the shot is most likely to miss. In high-pressure situations like penalty shootouts this could be a very risky strategy for the penalty-taker.

Interestingly, diving for the ball may not be a good strategy for a goalkeeper. An analysis of penalties (carried out by Michael Bar-Eli at Ben-Gurion University) suggests that the goalkeeper is most likely to save a penalty by staying in the middle of the goal. However, few goalkeepers choose this, as they feel they have to be seen to be trying to save the ball.



Goalkeepers find it hardest to save shots at the top corners, but penalty takers are more likely to miss the goal with these shots.



Goalkeepers do not have time to react to the ball, so they need to make a guess – and don't always get it right.

EXPLORING THE IDEAS EXPERIMENTALLY

Thinking about good strategies for taking and saving penalties requires an understanding of probabilities. An important idea in this session is that data can help us make predictions. Collecting more data can lead to better predictions, but cannot tell us what will happen or ensure that a goal is scored. In this session, students will collect their own data and use secondary data from observations of penalties.

Students start by watching some videos showing penalties and use a recording sheet to record which area of the goal the player aimed at and whether a goal was scored. The purpose of this is to give them a sense of how data from observations can be collected and organised.

Students can then move on to analyse typical data on penalties as shown on the data sheet below. They should consider how this information could be used to determine what appears to be the best area of the goal to aim at. They may want to work these out as percentages before coming up with a conclusion.

Finally, to emphasise the reason goalkeepers often jump the wrong way students could be given a challenge in estimation – to try to estimate and compare a typical human reaction time with the time taken for the ball to reach the goal.

TELLING A PHYSICS STORY

Repeated readings are often essential in physics in order to minimize the uncertainty of a measurement. In the case of penalties, it is essential to take a large number of readings because the outcomes differ from one run to the next. The more readings that are taken the more useful the calculated probabilities will be for making predictions, but probabilities cannot tell us what will happen or whether a goal is scored.

The penalty data can be analysed in different ways: one possibility is to calculate the percentage of goals scored in each area. Whether a goal is scored depends on the product of two probabilities – the probability of the shot being on target (i.e. not missing) and the probability that it goes in the goal (i.e. it is not saved). While a formal treatment of probabilities is not appropriate, students should see that success depends on a combination of these two factors. The higher and wider the ball is placed, the less likely the goalkeeper is to save it, but aiming further away from the goalkeeper also means that there is more chance of missing.

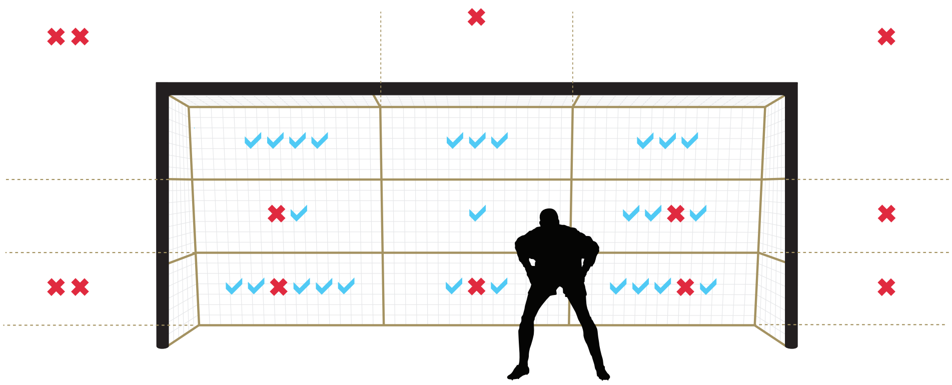
USING THE IDEAS ON THE PITCH

Students will be practising their penalty taking techniques, including a penalty shootout, and finding out what they think are the best strategies for where to aim the ball.

Typical results showing the numbers of penalty shots aimed at different areas of the goal and the outcomes. Note that the view of the goal shown is as it would appear to the penalty taker.

✔ Goal scored

✖ No goal (saved or missed)

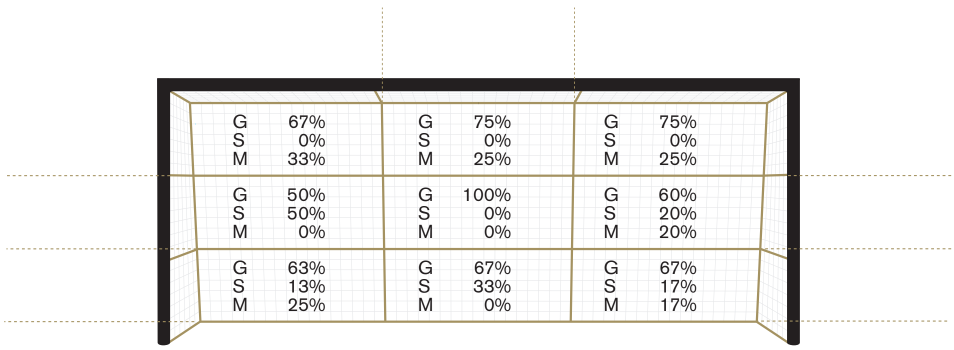


The data is expressed as the percentage of shots resulting in goals and those saved or missed for different areas of the goal.

G = Goal scored

S = Saved

M = Missed



CLASSROOM GUIDANCE

OBJECTIVES

Students should:

- Make predictions about the best place to aim for penalty kicks.
- Observe videos of penalties and record their observations.
- Analyse data about the outcomes of penalties.
- Draw conclusions from data and use these to suggest successful strategies for penalty takers and goalkeepers.
- Calculate time of travel of a ball from given data.

RESOURCES

Screen to show video of penalties

Physics activity sheet for recording observations and for secondary data

For each group:

- Paper, pencils, calculators
- Students' mobile phones with reaction timer app. (optional)

SUGGESTED STRUCTURE AND TIMINGS

5 mins — Introducing the session using video clips of penalties and discussing strategies.

10 mins — Observing video and recording observations.

15 mins — Analysis of secondary data on penalties.

5 mins — Calculation of the time for the ball to reach the goal.

10 mins — Class discussion of what might be the best strategies.

TEACHING POINTS

To stimulate discussion at the start of the session students could watch a video of a few penalties (e.g. part of a penalty shootout) and think about good and bad strategies for penalty takers and for goalkeepers. They can then think about how they might go about recording the observations in a systematic way. (Searching YouTube for penalty shootouts will identify a number of suitable examples – using one that includes slow motion repeats will be helpful in seeing the part of the goal aimed at.)

Students can now be introduced to the diagram on the physics activity sheet for recording their observations. This divides the goal into a grid of areas, and students should observe a number of penalties, recording the position of the shot and whether a goal was scored. Doing this themselves should help them to understand the secondary data later and they should appreciate that a small number of observations is not sufficient to draw conclusions when dealing with probabilities.

They can then move on to look at a larger number of results using secondary data on the activity sheet. There are different ways that they could summarise the data, but the pattern that emerges should suggests that the top corners are the places to aim to avoid a goalkeeper saving the shot, but are also those when the penalty taker is most likely to miss.

Finally they could use the information on the activity sheet to find the time it takes for a ball to travel to the goal in a penalty and to find their own reaction time. Comparing these shows how little time a goalkeeper has to react.

ON THE PITCH

These ideas will be relevant when students practise the following on the pitch:

- Improving their penalty kick technique.
- Disguising which way they will kick the penalty.
- Choosing a suitable spot in the goal and being able to hit that target.

SESSION 3

HOW CAN YOU ACCELERATE FASTER?

Footballers spend a lot of their time running, but in a very different way to an athlete running a race. In a football match, a player will sometimes be moving slowly and sometimes quickly, they will speed up and slow down, and will change direction.

Velocity is a measure of how fast something is travelling in a particular direction, and acceleration is a measure of how quickly a velocity changes. Measuring velocity and acceleration can identify the performance of a player and track improvements.

FOOTBALLERS IN ACTION

The ability to accelerate quickly in football is hugely important in order to evade defenders or keep up with attackers. Legs need to push with large forces on the ground, so they need to be very strong and the grip has to be very good. Footballers are becoming more athletic, with teams wanting very fast players to leave defenders behind and to launch counter attacks, but what form of athleticism is the most appropriate?

In football matches the ability to accelerate quickly is usually more important than the final top speed. In athletics, a top sprinter in a 100 metres race would take about 60 metres to reach their top speed. In football, most races are over 10 to 15 metres, though sometimes longer if a team breaks with a rapid counter attack. Sprinters run down a straight track without having to change direction and this is rarely the case in football.

Usain Bolt has talked about his ambition to play football, but does he have the right qualities? One of the fastest premiership footballers is Theo Walcott, whose top speed has been measured at 10.4 metres per second. This is rather slower than Bolt who can top 12 metres per second (nearly 30mph!), but Bolt has a much more upright running style and longer strides than Theo Walcott. It is much harder to change direction rapidly and to control a football when running flat out like this. Footballers change direction all the time and need what is known as 'first-step quickness' – the ability to rapidly change their motion.

When an attacking player is running a long way with the ball, being able to run as fast as possible is important.

When a player tries to get to a ball first from a standing start, it is *acceleration* that is important.

EXPLORING THE IDEAS EXPERIMENTALLY

Talking about a footballer as being able to 'move fast' is ambiguous – it could mean that they have a high maximum velocity when they run, or it could mean that they accelerate quickly. A simple way of modelling moving objects and timing their motion is to use a marble rolling down a slope.

When the direction of a moving object does not change, such as a marble rolling down a slope, it is not so important for students to distinguish between speed and velocity. However, footballers often change direction when they are running, and this means that they need to accelerate (in a different direction) even if they are running at the same speed.

Students can explore the ideas of velocity and acceleration by timing a rolling marble at different points down a slope. They can make estimates of its average speed and its top speed, and by changing the slope they can relate their findings to different accelerations.

As a challenge for students, they can design a demonstration to show the difference between velocity and acceleration. A piece of cardboard is split so that different angle slopes can be made. They can see if they can find out how to make a marble with low initial acceleration (released from a shallower slope) catch up with a marble with higher initial acceleration (released from a steeper slope).

TELLING A PHYSICS STORY

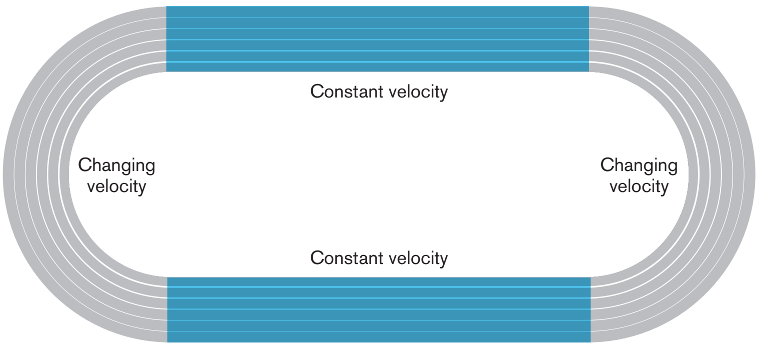
To find the velocity (or speed) of a marble rolling down a slope it is necessary to measure the distance the marble has travelled and the time taken to travel that distance. Since the marble accelerates down the slope, its velocity changes, and so dividing distance by time gives the average velocity over this distance. If the acceleration is constant, then the average velocity is the same as the instantaneous velocity at the midway point.

In the demonstration to show the difference between velocity and acceleration, the marble released on the steeper slope has a greater acceleration than the one released on the shallower slope. However, it will not necessarily have the higher top speed: if the ball on the shallower slope is released from further up then it will accelerate for longer.

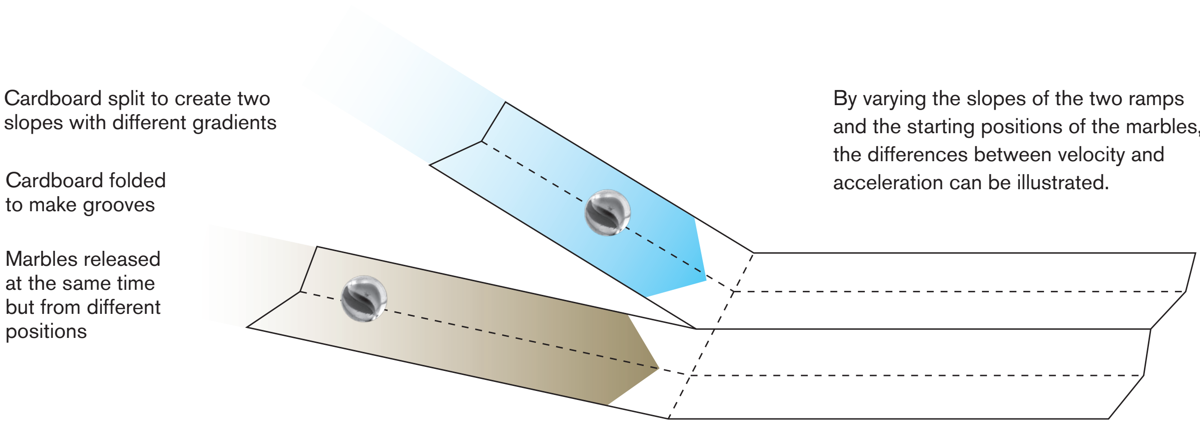
The top speed for both marbles will be at the bottom of the slope. When they reach the level section, they will gradually get slower (decelerate). If one marble overtakes the other on the level, this is because it has a greater top speed and not because it is still accelerating.

USING THE IDEAS ON THE PITCH

Students will be practising their running techniques, and measuring their times over a range of distances. They will also look at judging when to run to avoid being offside.



A runner can run around a track with a constant speed, but the velocity will change. Velocity is speed in a particular direction, so if the direction changes then the velocity changes.



By varying the slopes of the two ramps and the starting positions of the marbles, the differences between velocity and acceleration can be illustrated.

CLASSROOM GUIDANCE

OBJECTIVES

Students should:

- Use appropriate terminology to describe the motions of objects.
- Distinguish between speed (or velocity) and acceleration.
- Investigate and measure the motion of a rolling marble.
- Design a demonstration to show the difference between acceleration and top speed.

RESOURCES

For each group:

- Wooden board or runway at least one metre long
- Sticky labels or tape to mark distances
- Two marbles, metre rule, stopwatch
- Cardboard, cut, scored and folded as on previous page
- Calculator, paper, pencils
- If available: students' mobile phones with stopwatch app (lap time function) and video function (slow motion playback)

SUGGESTED STRUCTURE AND TIMINGS

5 mins — Introducing how the motions of footballers can be described.

10 mins — Discussion on how to plan the practical activity.

20 mins — Carrying out the practical activity and designing the demonstration.

10 mins — Bring the whole class together to share ideas and relate to footballers.

TEACHING POINTS

The extent to which the use of terminology is emphasised will depend on the background of students. Some might be expected simply to distinguish between speed and acceleration, while others might also distinguish distance and displacement, and speed and velocity.

Students could start simply, marking off distances of 0 cm, 50 cm and 100 cm on a slope, and timing how long a marble takes to travel the first 50 cm and the second 50 cm. From this they can work out average velocities and find that the ball is accelerating.

Next they can try to estimate speed of the ball when it is moving fastest at the bottom of the slope. Now they need to use as small a distance interval as possible (e.g. 20 cm), although this makes timing by eye more difficult. The difference between top speed and average speed is important.

Students could find the times for each interval using a stopwatch phone app with a lap time function. Alternatively, using a conventional stop watch they could obtain times by doing multiple runs. Another method would be to use a phone video: if the frame rate is known, then the speed can be calculated by observing the distance between frames.

The 'split cardboard' should be pre-cut and folded to create two grooves for the balls. Students can explore the combinations of slope and release point from which the ball from the shallower slope catches up and passes the ball from the steeper slope, and try to find what the 'rule' is.

ON THE PITCH

These ideas will be relevant when students practise the following on the pitch:

- Running on their toes and running with the ball under control.
- Explosive starts and improving their acceleration.
- Knowing how to get ahead of an opponent who has a greater acceleration.
- Beating the offside trap in a free kick.

SESSION 4
WHAT MAKES A GOOD PASS?

When a player kicks a ball, usually it is a pass to another player. There are shots at goal and kicks to clear the ball, but what maintains the pace of a game are good passes.

A pass needs to be well-timed and well-positioned. Getting the ball to the right place at the right time depends on the forces involved: the initial force that makes the ball move and the forces that act on the ball to slow it down.

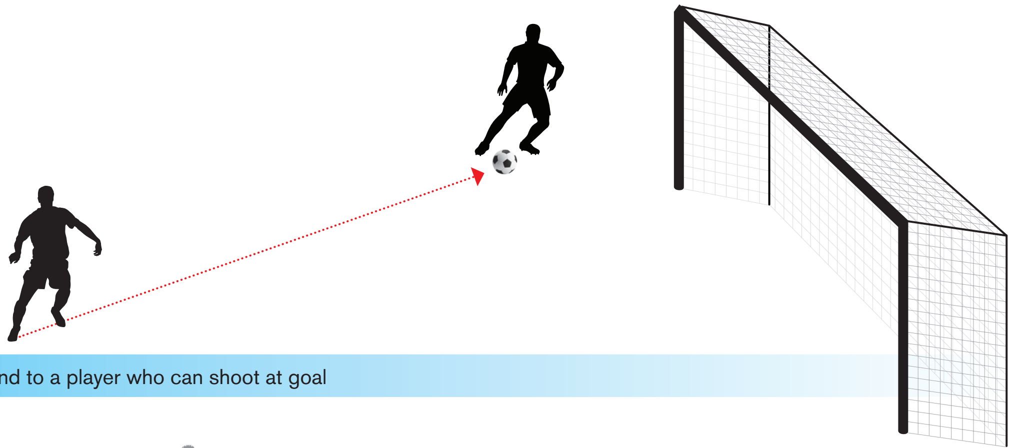
FOOTBALLERS IN ACTION

Footballers use different kinds of pass for different situations. They include short and long passes, along the ground or in the air, and passed directly to a player or aimed some distance in front of a running player.

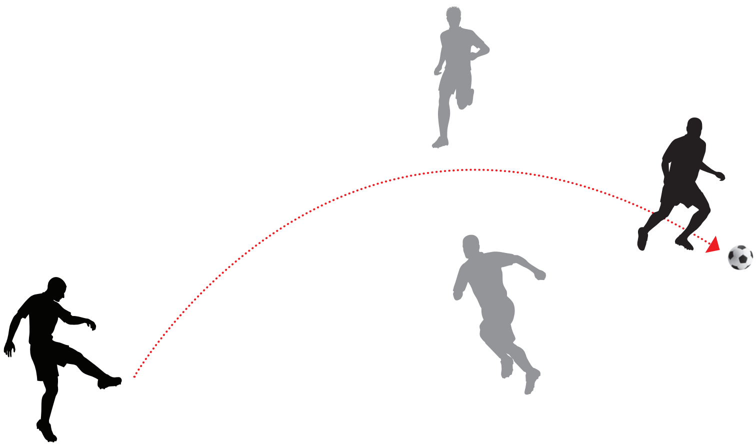
A pass straight to a teammate should be accurate and 'well-weighted' – fast enough to get there without being intercepted but not too fast for the teammate to control. A short through-ball on the ground might be used, for example, in an opposing penalty area, to another player who then scores.

Some passes go ahead of the teammate, for them to run onto. Again this has to be done with just the right speed in the right direction so that the receiving player doesn't have to change speed or direction. Passing ahead of a teammate is a very good way to get through defences; the attacking player can receive the pass or shoot without slowing down.

Passing over long distances is usually in the air. There is a limit to how far any footballer can pass a ball effectively on the ground and there are often opposition players in the way. Kicking the ball over a long distance in the air might be done, for example, as a long pass out wide to the receiving player or as a cross pass into the box for the teammate to run into and head the ball at the goal.



A short pass along the ground to a player who can shoot at goal



A longer pass in the air to avoid the opposing players

EXPLORING THE IDEAS EXPERIMENTALLY

When passing the ball, it is often important to get it from one position to another as quickly as possible. This session focuses on whether it is better to pass along the ground or in the air. Investigating this in the classroom using footballs is not practicable, so instead students will model the different types of passing using beanbags to represent footballs. One important limitation of this modelling is that beanbags will slide while footballs roll.

Students need to think about designing a demonstration to show whether it is quicker to pass a ball over a short distance on the ground or in the air. One student can slide the beanbag along the ground towards the feet of another student, while a third student times how long it takes. This can now be repeated by throwing the beanbag from ground level to arrive at the feet of the other student.

They can now try to see what happens when the distance between the thrower and the receiver is changed. They can also try using different floor surfaces (for example, carpet and vinyl tiles) to model the effects of passing the ball in different conditions (for example, dry grass, wet grass and mud).

TELLING A PHYSICS STORY

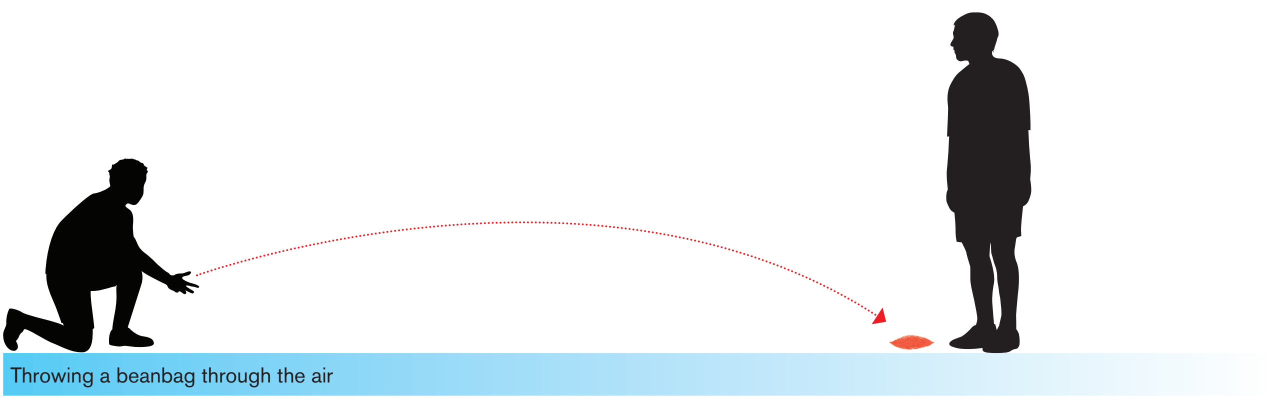
The important point that should emerge is that a pass on the ground can get to a player's feet quicker than one in the air. The idea that the shortest distance between two points is a straight line can be reinforced here. Depending on the floor covering, the practical activity may indicate that there is a limiting distance. However, students will probably have had experience of kicking a ball on different surfaces – from muddy pitches and long grass (where the ball may travel only a short distance along the ground) to Astroturf and indoor sports halls (where the ball can easily go from one end to the other). The factors affecting the decision about whether to pass along the ground or in the air will therefore depend on the context.

Representing different stages of the ball's movement using force diagrams shows how after the initial kick, there are forces acting in the opposite direction to the movement of the ball (friction on the ground and drag in the air). An important idea is that there are no forces acting in the direction of motion of a ball once it is kicked.

USING THE IDEAS ON THE PITCH

Students will be practising different kinds of pass, and finding out the maximum distance they can pass along the ground before they need to pass by kicking the ball in the air.

Which takes less time:
sliding a beanbag across the floor
or throwing it through the air?



CLASSROOM GUIDANCE

OBJECTIVES

Students should:

- Use modelling to demonstrate the relative times it takes for a ball to arrive at a teammate's feet, depending on the type of pass.
- Identify the forces acting on an object as it moves along the ground or in the air.
- Draw and label force diagrams using conventions presented.
- Relate the practical demonstration to the way that footballers pass the ball.

RESOURCES

For each group:

- Beanbag (or two beanbags) and stop watch, metre rule, paper, pencils
- Access to shiny floor covering, so beanbags will slide (and other floor coverings if possible)
- If available: students' mobile phones with video function.

SUGGESTED STRUCTURE AND TIMINGS

5 mins — Introduce passing on ground and in the air.

10 mins — Discuss with students how to plan the design of their demonstration.

15 mins — Students work in groups to design and carry out the practical.

10 mins — Explain to students how to represent forces on beanbag and students draw diagrams.

5 mins — Share ideas and demonstrations and relate to football.

TEACHING POINTS

CAUTION: To avoid back injury, students should kneel when they are doing this activity. They can then slide or throw the beanbags without bending over.

To start the session, you could start by asking students to discuss in groups about what makes a good pass and collect these ideas. An important question is when particular types of pass are used and why. They could then try to predict whether it is quicker to pass along the ground or through the air, and to plan an investigation using beanbags.

A suitable method would be for students to work in a group of three. Student A kneels and student B stands about three metres away. Student C measures the time for A to slide a beanbag along the floor to B. This is repeated with A throwing it underarm to land at B's feet, starting with their hand holding the beanbag on the floor. Alternatively, with two bean bags, A slides a beanbag and C throws a beanbag at the same time, and B decides which gets there first. Students should repeat a few times to confirm their results.

Students can then repeat for different distances (depending on space available and how responsible they are) and for different surfaces.

As an alternative to using beanbags, students could use blow balls (along with safety glasses) as in Session 1.

You may wish to spend longer on the practical activity and omit the activity on identifying forces. One crucial idea is that there is no force in the direction of travel of the beanbag once it has been released from the hand.

ON THE PITCH

These ideas will be relevant when students practise the following on the pitch:

- Passing a ball accurately on the ground over greater distances.
- Establish over what distance each player needs to loft the ball to get the distance.

SESSION 5
FORCEFUL TACKLING

Footballers need to develop important skills in being able to tackle effectively as well as safely. Mistimed tackles can result in injury, so knowing what causes most damage is essential in avoiding getting injured oneself.

When objects collide, it is the forces between them that make them slow down. These will have the greatest effects when they are concentrated over a small area; so to reduce harm it is important to try spreading out these impact forces.

FOOTBALLERS IN ACTION

Football is a contact sport and injuries can happen. Intercepting a pass or getting to the ball before an opposing player are relatively unlikely to cause any problems. However, injuries are more likely when two players are trying to kick the ball at the same time during a tackle.

What is important is that tackles are well-timed and the feet are close to the ground. In this case, there is still relatively little chance of injury. However, mistimed tackles and those where a foot is well above the ground are more dangerous, particularly when the studs are likely to make contact.

Shins and ankles are particularly vulnerable because they are close to swinging boots and they are bony areas of the body. A kick on the calf from behind is less likely to cause major damage. So, footballers protect themselves with shin pads and, in some cases, with ankle guards.

In a 50:50 challenge, both players are trying to kick the ball at the same time, and care needs to be taken to avoid injury

In a sliding tackle, both feet are kept close to the ground to avoid injury from the studs at the bottom of the boot

EXPLORING THE IDEAS EXPERIMENTALLY

Referees are quick to penalise players who tackle dangerously in ways, where their studs could injure other players. In this session students will explore different types of impact and why studs can be particularly dangerous. To model the effect of impacts on the human body, play dough can be used. The effects of the impact can be observed from the indentations made in the play dough.

Forces are more likely to damage something if they are concentrated over a smaller area. The challenge for students in this session is to show how shin pads work and why a studs-up tackle is so dangerous. They should design a convincing demonstration to illustrate the effects of concentrating or spreading out the area of impact.

In looking at collisions, the focus is on impacts rather than the steady application of a force. So, this can be explored by dropping objects onto a surface and assessing the damage caused.

The basic method is to drop a heavy weight (e.g. a steel ball) from a consistent height onto Lego or similar bricks that are resting on play dough. The Lego bricks can be orientated differently to enable the effect of different surface areas to be explored for the same impact force. By using a cardboard tube, a heavy ball can be safely dropped onto the bricks.

Samples of play dough or close-up images of the damage can provide qualitative evidence, but students could also try to find more quantitative way of assessing the damage by measuring the depths of the impacts.

TELLING A PHYSICS STORY

The size of the indentation produced in the play dough is dependent on the impact force (this factor is the same in the activity described since the same object is dropped from the same height) and on the surface area of the brick. The indentation is greater with a greater impact force and with a smaller surface area. The term 'pressure' is often used to refer to the value of force per unit area, but strictly speaking this only applies to liquids and gases. For solids the correct term is 'stress', thus the greater the stress on the surface the greater the indentation.

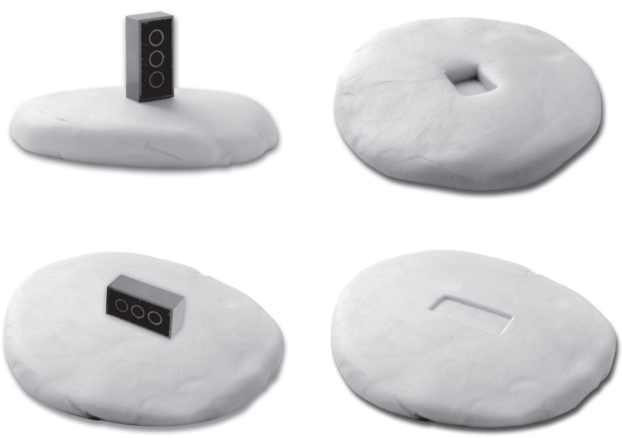
The activity is intended to model the kick of a boot on another player's leg, and so this is not the steady application of a constant force, but rather an impact where the force causes the impacting object to decelerate. For a smaller contact area, the retarding force of the surface on the object will be smaller. This means that the object will decelerate more slowly and travel further into the surface before it stops.

USING THE IDEAS ON THE PITCH

Students will be practising safe ways of getting or retaining possession of the ball, with an emphasis on the ways that dangerous collisions can be avoided.

A heavy ball is dropped down a cardboard tube onto a Lego brick resting on play dough.

By changing the orientation of the Lego brick, the damage caused by impacts over different surface areas can be explored.



CLASSROOM GUIDANCE

OBJECTIVES

Students should:

- Recognise that certain factors increase the risk of injury from tackling.
- Design a practical demonstration that shows these effects, qualitatively and quantitatively.
- Explain how a reduced impact area increases the potential damage done..
- Relate the practical demonstration to safe and dangerous play.

RESOURCES

For each group:

- Cardboard tube (e.g. poster tube or kitchen roll tube) and weight to drop down tube (e.g. heavy steel ball, cricket/hockey ball, laboratory masses, small drinks bottle filled with water)
- Rectangular 'eight-stud' Lego block (and optional thin block with flat top that sticks onto the 'studded' tops)
- Lump of play dough or Plasticine (to make a disc, approximately 10 cm diameter and 2 cm thick), equipment tray, ruler (marked in mm), matchsticks, paper, pencils
- If available: students' mobile phones with video function.

SUGGESTED STRUCTURE AND TIMINGS

5 mins — Introduce safe and dangerous ways to tackle.

5 mins — Discuss with class how to design demonstrations to show these ideas.

20 mins — Students in groups build and test their demonstrations.

15 mins — Bring the whole class together to share results and ideas and relate to how footballers avoid injuries.

TEACHING POINTS

CAUTION: Students should take care that the ball does not roll off the bench when it could injure a foot. They should use a cardboard tube to guide the ball and do the activity in an equipment tray. Note that some children with wheat gluten allergies may be allergic to play dough.

The opening class discussion on tackling safely should lead on to students considering why shin pads are worn and a studs-up challenge is particularly dangerous. From this, they can then suggest ways that they could test ideas of the effects of concentrating forces over different areas.

Both play dough and Plasticine are suitable materials, though Plasticine is more resistant and may require a heavier object. The crucial idea is to have the right combination of weight of object, height of tube and resistance of material, so that the impacts over different surface areas can be explored with some attempt to measure the depth of impact.

With play dough, for example, an adult cricket or hockey ball (150 g) dropped over a height of 90 cm gives a good spread of indentations whilst a smaller steel ball (500 g) only needs a 20 cm height. If the tube is held resting on the play dough then the ball stays still after impact.

The results that students present can be either qualitative or quantitative. They should note the difficulties of measuring the indentations directly with a ruler, since rulers do not start at zero, therefore matchsticks or pieces of card can be used to measure the depth.

ON THE PITCH

These ideas will be relevant when students practise the following on the pitch:

- Taking each other on, trying to get past with the ball.
- Jockeying an opponent to prevent them getting past with the ball.
- With appropriate coaches/teachers only: safe ways of tackling.

SESSION 6

HOW CAN YOU CONTROL A BALL EFFECTIVELY?

Football often involves trying to control a moving ball: the aim may be to stop it or to redirect it. How the ball is controlled depends on which part of the body is used, such as the chest or head, and how much the ball is actively 'cushioned' by the player.

The 'bounciness' of a ball depends on the material it is made of, as well as its structure and the pressure to which it is inflated. How much a ball bounces from a surface also depends on the material and the structure of the surface itself.

FOOTBALLERS IN ACTION

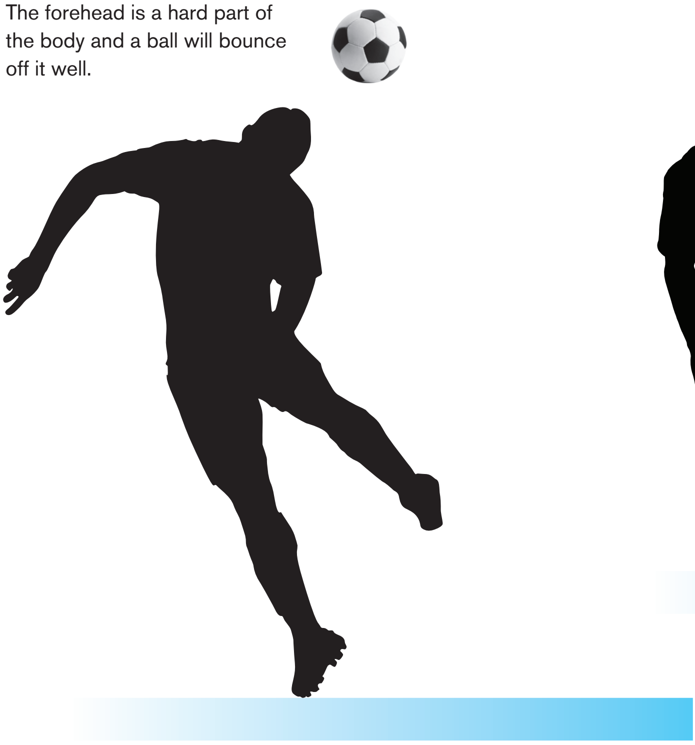
Some parts of the body will tend to make a moving ball rebound faster than others. The 'sweet spot' on the foot (the bone just above the big toe), the knee, and the forehead are all hard and bony, and the ball will bounce off them well.

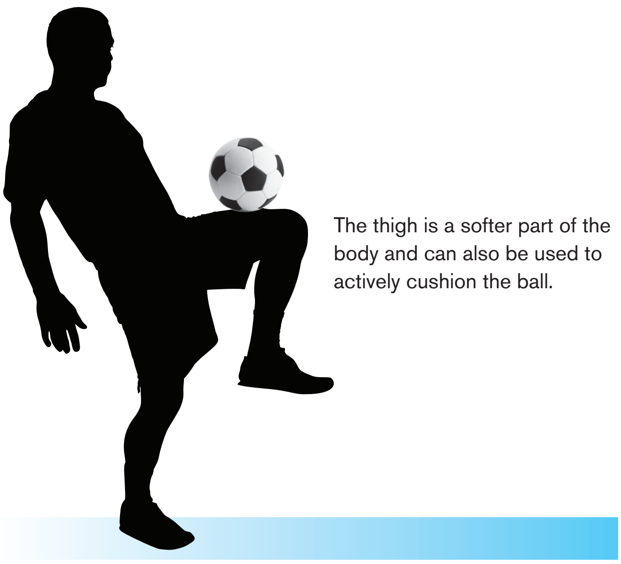
Other parts of the body such as the thigh, the chest and the instep of the foot (the large, flat area that faces the other foot when standing feet together) are softer. To control the ball by slowing it down it is easier to use a soft part of the body.

In general then, because the forehead is hard, the ball will bounce off it more than off the chest, which is softer. However, another factor affects how much the ball bounces. Footballers can 'actively cushion' the ball with any part of their body to minimize the rebound. They do this by moving that part of their body backwards slightly, making the ball slow down and stop.

By cushioning the ball, players can also use the hard parts of their body, the foot or forehead, to slow down the ball. In contrast, for maximum rebound speed, a footballer makes that part of their body more rigid, to kick or head the ball as fast as possible.

The forehead is a hard part of the body and a ball will bounce off it well.





The thigh is a softer part of the body and can also be used to actively cushion the ball.

EXPLORING THE IDEAS EXPERIMENTALLY

Controlling a ball requires a footballer to perform a complex series of actions. Here the focus is on what affects how much the ball bounces off a player. To model different parts of the body different surfaces are used, and to model 'tensing and cushioning' different structures are used.

The challenge for students in this session is to produce the most convincing demonstration of these effects, and to find the best way of minimizing the rebound. They could try using different types of ball dropped onto different surfaces and seeing which combination produces the best and worst bounces. By dropping the ball from a fixed height each time they can measure how high it bounces: the higher the ball bounces, the faster it must have bounced off the surface.

They can then go on to look at different kinds of structures, by using a chair with initially four legs on the floor and then with a wad of paper put under one of the legs to make it wobble.

Students could also try looking at the pattern for different heights. Is the height of the bounce proportional to the drop or is there a more complex relationship?

TELLING A PHYSICS STORY

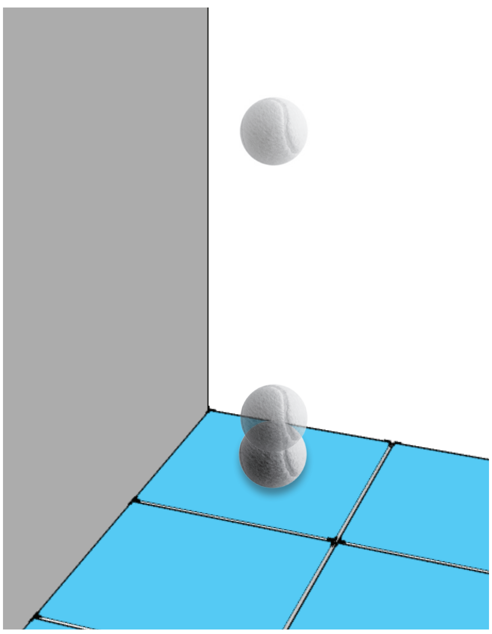
When a ball hits another object, different surfaces and structures of the object will affect how the ball rebounds. A ball dropped onto a concrete floor bounces better than one dropped onto carpet; this is related to the hardness of the surface. A ball dropped onto a wobbly chair bounces less well that one dropped onto a stable chair; this is related to the rigidity of the structure.

In a perfectly elastic collision, the ball rebounds at the same speed. As it travels towards the surface, all of the molecules of the ball are travelling in the same direction; after collision they travel at the same speed in the opposite direction. In a non-perfect collision, the ball travels away more slowly.

The reason is that some of the 'organised motion' of the molecules in the ball has been lost, but the random or irregular motion of the molecules in the ball and the ground has increased. There is less energy in the moving ball, but the ball and ground become a little warmer. A similar mechanism accounts for the way that a ball bounces less well off a wobbly structure.

USING THE IDEAS ON THE PITCH

Students will be practising how to receive a ball using different parts of their body (feet, thigh, chest and head), either to stop the ball or to change its direction.



A ball will bounce better on a hard surface (concrete is better than carpet) and a rigid structure (a stable chair is better than a wobbly one).

CLASSROOM GUIDANCE

OBJECTIVES

Students should:

- Recognise that different parts of the body can be used to control a moving ball, either to stop it or redirect it.
- Explain how controlling the ball depends on the part of the body used and how much the ball is actively cushioned.
- Design a demonstration that shows how much a ball rebounds from different surfaces and structures.
- Relate the demonstration to the way that footballers control the ball.

RESOURCES

For each group:

- Selection of balls (e.g. tennis balls or table tennis balls)
- Plasticine (optional)
- Metre rule, paper, pencils, calculator (optional)
- Access to different floor coverings e.g. hard, carpet, newspapers, large book
- Access to furniture with different rigidities e.g. table, desk, chair (with and without a wad of paper under a leg)
- If available: students' mobile phones with video function.

SUGGESTED STRUCTURE AND TIMINGS

5 mins Introduce how footballers control a ball.

10 mins Discuss with class how to design demonstrations to show these ideas.

20 mins Organise students into groups to design the practical demonstrations.

10 mins Bring the whole class together to share their ideas and demonstrations, and relate to what footballers do.

TEACHING POINTS

In the class discussion at the start of the session, the main idea that students should grasp is that different techniques are used to control the ball in different ways. It is important that they can make the distinction between the contact surface and the rigidity of the structure that the ball bounces off.

Students should try different kinds of balls and at different heights (a good height for a tennis ball is 1 metre and for a table tennis ball 0.5 metres). Measuring the height of the bounce against a metre rule by eye could lead to a discussion of experimental uncertainty and students could explore the use of video (e.g. on a mobile phone) as a way of reducing this. They should find that some surfaces will absorb the impact better than others and that if the structure as a whole can move, then it will also absorb some of the impact.

In thinking about what happens during the bounce of a ball, it may be helpful for students to hold a tennis ball in their hand and push it against a surface, and then do the same with a ball of Plasticine, so that they can feel that different things interact differently with the surface.

As an extension, they could try doing calculations of the coefficient of restitution, which is the ratio of the speeds of the ball before and after it bounces (they could work out the speeds from the height of the ball).

ON THE PITCH

These ideas will be relevant when students practise the following on the pitch:

- Controlling the ball with different parts of the body, including softer parts e.g. chest and thigh.
- Actively 'cushioning' the ball with different parts of the body.
- Safely heading the ball.

SESSION 7

USING YOUR BODY FOR BALANCE AND STABILITY

Footballers use their whole body in order to run, turn, jump, kick, tackle, head or throw as effectively as possible. High performance in any of these areas is a combination of body shape and technique.

An object will topple if its centre of mass in not above its base. Balance and stability are concerned with maintaining the position of a body and are affected by changes to the centre of mass.

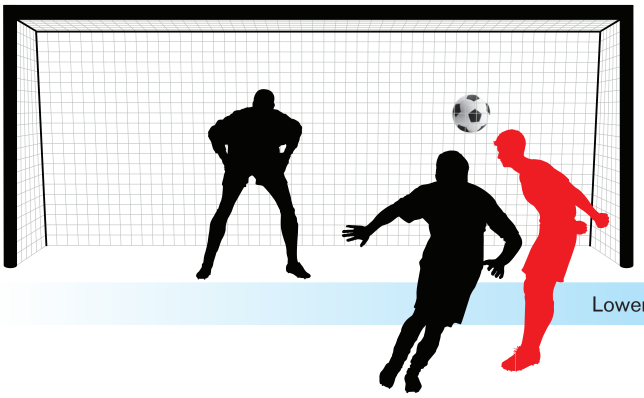
FOOTBALLERS IN ACTION

When a player accelerates from a standing start, the body tends to adopt a low position, becoming more upright when running at top speed. Changing direction is also accelerating, and the same low body position is required, though the arms are used differently to provide balance. Skilful players manage to do this really quickly and remain balanced even when controlling the ball at the same time.

The correct body position is also important during contact with other players. It is easier to be pushed over when a player is standing upright – adopting a low position is more stable.

Winning a header often requires the player to jump as high as possible. By lowering the arms and legs whilst in the air, a player can jump higher and get a better chance of winning the ball.

So, by skilful positioning of the body, players can run faster, accelerate and change direction more quickly, jump higher and make their bodies more stable during contact.



Lowering the arms while jumping up can increase the 'hang time' in the air.

Adopting a lower position, with feet apart, provides more stability when shielding the ball

EXPLORING THE IDEAS EXPERIMENTALLY

Intuitively, we think of shorter players as being quicker at turning, more balanced and more stable when contact occurs. This is related to their lower centre of mass. An interesting way of modelling the effects of changing the centre of mass is to use a cardboard drinks cartoon containing water.

Students should design a demonstration that shows that, in general, objects with a lower centre of mass are more stable. The idea is to vary the centre of mass of an object and to measure the tipping angle, the angle at which it tips over when gradually tilted. The centre of mass of the drinks carton can be easily varied by filling with different amounts of water.

The challenge for students is to find the tipping angle for different amounts of water and then to relate this to the position of the centre of mass. The mass of the carton is relatively small compared to the water, so it can be ignored except when there is minimal or no water in it. Students find that the lower the centre of mass, the greater the angle that the carton can be tipped before it falls over.

However, in football, players are not static objects with a fixed centre of mass, but actively control their bodies. So a second important idea here is that when an object is moving adjustments need to be made to the centre of mass to keep the object balanced. Students can try balancing a metre rule vertically on a finger, and see the difference having a lump of play dough stuck to the rule first near the top and then near the bottom of the rule, makes.

TELLING A PHYSICS STORY

The surprising result here is that the tipping angle for the empty carton is very similar to that of the full carton, and that the tipping angle is greater when the carton is partially filled with water. This is because the centre of mass is highest for the empty and for the full container, but adding water to the empty container causes the centre of mass to be lower. It is the position of the centre of mass that determines the tipping angle, and so even though the full carton has a greater mass than a partially full one, its tipping angle is less. This is the reason why players lower their body when they are shielding the ball.

Trying to balance the metre rule can also lead to an unexpected outcome. It is easier to balance the metre rule when the centre of mass is higher (the play dough is at the upper end). The difference here from the first activity is that movement is involved. This explains why it is easier to keep one's body balanced with arms outstretched than to the side.

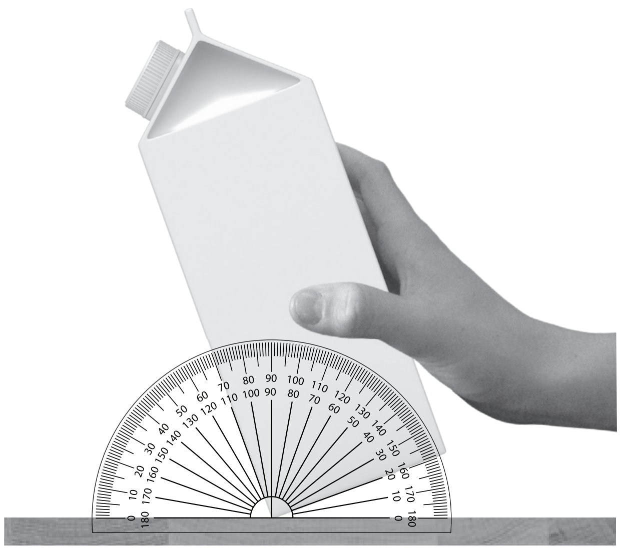
USING THE IDEAS ON THE PITCH

Students will be practising how to run and how to dribble with the ball, while changing direction frequently. This requires keeping a low body position to maintain balance and stability.

BEFORE

AFTER

Initially, the carton is filled with a litre of water. Water is then emptied out (100 ml or 200 ml at a time) into a measuring jug to give equal intervals for the independent variable.



CLASSROOM GUIDANCE

OBJECTIVES

Students should:

- Recognise that the stability of objects is dependent on several factors, including how the mass is distributed within the object.
- Design a practical demonstration that shows this effect.
- Identify the differences in effect between an inanimate object and an active person in balancing.
- Relate the practical demonstration to the way that footballers move in different situations.

RESOURCES

For each group:

- Empty cardboard orange or milk carton (one litre, square or rectangular based, must have re-sealable screw top)
- Measuring jug (one litre), semi-circular protractor, paper, pencils
- Lump of Plasticine or play dough (to make a ball approximately 8 cm diameter)
- Metre rule
- Equipment tray (optional)
- If available: students' mobile phones with video function (ideally with slow motion playback).

SUGGESTED STRUCTURE AND TIMINGS

5 mins Introduce how footballers adjust their bodies for different situations.

5 mins Discuss with class how to design demonstrations to show stability.

20 mins Students in groups investigate tipping angles for cartons.

5 mins Balancing metre rule activity.

10 mins Bring the whole class together to share results and ideas.

TEACHING POINTS

The carton can be filled with one litre of water to start with, and this can gradually be reduced in intervals of 100 ml or 200 ml at a time by pouring into a measuring jug to give equal intervals for the independent variable. Emphasise to students that they need to make sure that the screw top is put back on securely each time after they have poured water out. If you are worried about spills, they could do the activity in an equipment tray.

Students may need support in using the correct scale of the protractor to measure the angle. Tipping the carton as slowly as possible will help to pinpoint the tipping angle. These cartons effectively pivot at about the right height to allow the protractor to rest on the table. Students should take three measurements for each amount of water and then take an average. There are opportunities here to discuss ideas of accuracy and precision, and whether these could be improved.

In the second practical, students should squash a large lump of play dough or Plasticine around a metre rule, about 20 cm from one end. With the lump at the top end, students try to balance the rule vertically on one finger. Then, turning the rule upside down, they again try to balance it on one finger.

Pooling the class's experiences together should enable the general picture to emerge and to begin to answer the question is of whether or not objects with a lower centre of mass are more stable.

ON THE PITCH

These ideas will be relevant when students practise the following on the pitch:

- Changing direction quickly, with and without the ball.
- Paying more attention to body movements when practising any skill.
- Trying to repeat any movement performed with its mirror image, eg kicking with the other foot.

SESSION 8

HOW CAN YOU SPIN AND BEND THE BALL?

Footballers sometimes kick across the ball, rather than straight through it, to impart spin on the ball. They do this either to control how it moves through the air or to actively make it follow a curved or bent path.

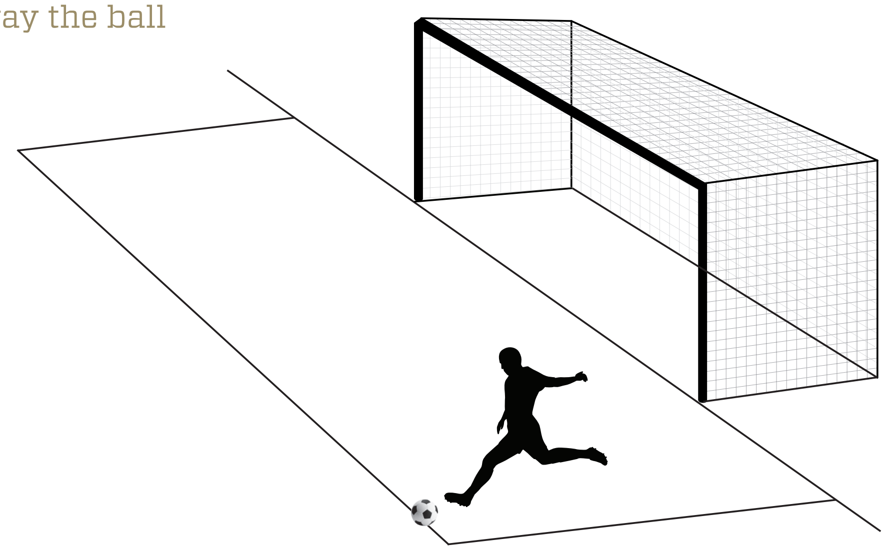
When a ball travels through the air it is slowed down by air resistance. If the ball is spinning, the forces of the air acting on it are different on different positions around the ball. These forces affect the way the ball moves through the air.

FOOTBALLERS IN ACTION

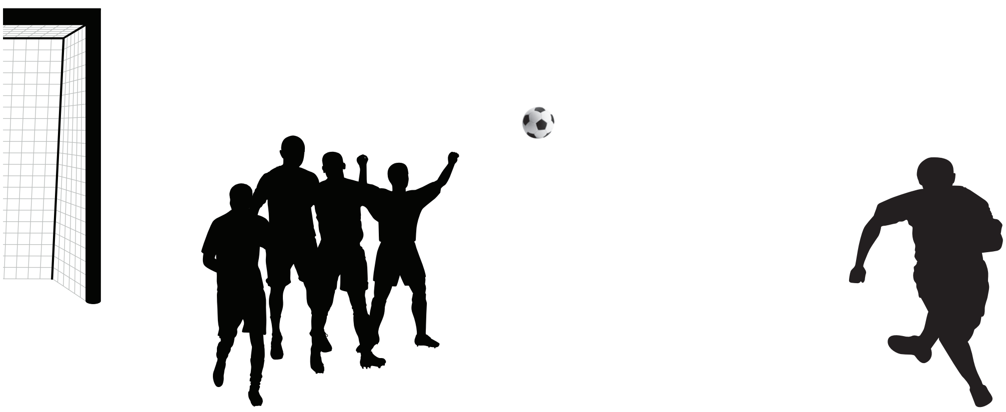
Sidespin arises naturally from an angle kick using the foot's 'sweet spot'. It is commonly used by footballers for in-swinging corners, crosses away from the goal to an oncoming forward, and balls down the touchline. The sidespin and curved path can be exaggerated in the classic case of bending a free kick. The outside of the foot can also be used to curve the ball, but in the opposite direction.

Backspin can be used to pass or cross the ball with a flatter trajectory over a long distance, so that it gets there quicker. It often arises when players are kicking for distance and the ball is rolling towards them and when they are trying to chip the ball.

Specialist free-kick takers can also impart topspin on the ball to get it over a wall of players and back down under the crossbar, although more often it occurs as the result of volleying a ball.



To achieve the maximum distance, a goalkeeper taking a goal kick will try to avoid any sidespin.



A player taking a free kick may aim to maximise sidespin in order to bend the ball around the wall of opposing players.

EXPLORING THE IDEAS EXPERIMENTALLY

Putting a spin on a football by kicking it requires a good deal of skill and a lot of practice is needed to produce consistent results. In this session, a spinner made from expanded polystyrene cups is used to model a spinning football to see how the spin affects its motion. The spinner can be launched by using a stretched rubber band.

The challenge for students is to design a demonstration to show how backspin, sidespin and topspin affect the way that the object moves through the air. Two expanded polystyrene cups are taped together at the base to form the spinner, and then two elastic bands are tied together. The elastic is held on the spinner where the cups join and wound round a few times.

To produce backspin, the free end of the elastic should be at the bottom pointing away from the student launching it. The spinner can now be 'fired' like a catapult, and will spin in the air as it travels. Backspin creates lift, thereby making the cups initially deviate upwards.

Topspin can be created by using the same method but turning the arrangement upside down. Sidespin can also be demonstrated by holding the spinner upright, with the free end of the rubber band to either the right or the left of the spinner.

Students could try other kinds of cups and could vary the launching technique. If they have a camera or phone with a video function, they could try varying the position of the camera for each shot, in order to capture the finer detail of how each type of spin produces a different motion.

TELLING A PHYSICS STORY

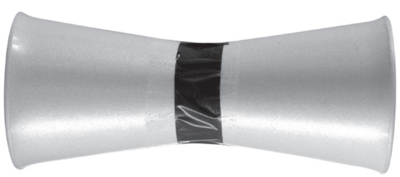
The spinner made from polystyrene cups works well as a model for investigating the effects of spin because it has a relatively large surface area compared to its mass. This means that the effects of spin on its movement will be more pronounced than for an object such as a football.

When the spinner is moving forward through the air and spinning, different parts of it will be moving at different velocities relative to the air. For example, if it has backspin, the lower surface of the spinner is travelling more quickly through the air than the upper surface. This means that there is a difference in friction between the lower and upper surfaces, and the effects of this on the molecules of air leads to a difference in pressures. This pressure difference causes a force that acts upwards on the spinner, and so the spinner bends upwards. A footballer can use backspin to make the ball travel further, since the upward bend of the ball counteracts the effect of gravity pulling the ball down.

USING THE IDEAS ON THE PITCH

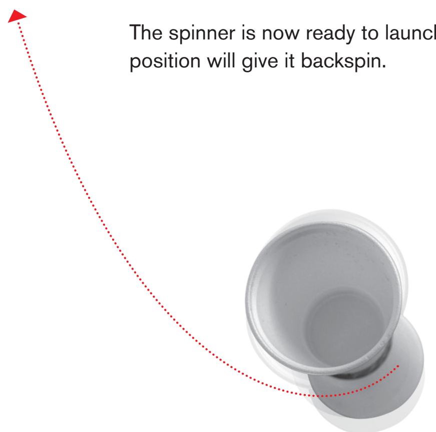
Students will be practising different ways of kicking the ball in order to give it spin – from the natural sidespin that comes from an angle kick to the more difficult technique for topspin.

The spinner is now ready to launch – holding the spinner in this position will give it backspin.



The first step is to tape two expanded polystyrene cups together to make the spinner.

Next, join two strong elastic bands together with a knot.



When a spinner with backspin is launched, it will bend upwards in the air as it travels forward.

CLASSROOM GUIDANCE

OBJECTIVES

Students should:

- Recognise that spherical or cylindrical objects can be made to spin and this affects their movement through the air.
- Design a demonstration that shows these effects using video.
- Explain how spin can be imparted on a spherical or cylindrical object and why it affects the motion.
- Relate the demonstration to the way that footballers spin and bend the ball in different situations.

RESOURCES

For each group:

- Two or more polystyrene or polythene cups to make the spinner
- Sticky tape, two or more elastic bands, paper, pencils
- Access to cling film (optional)
- Safety glasses
- If available: students' mobile phones with video function (ideally with slow motion playback) – video recording is particularly useful for this session.

SUGGESTED STRUCTURE AND TIMINGS

5 mins – Introduce how footballers spin and bend the ball.

5 mins – Discuss with class how to design demonstrations to show these ideas.

20 mins – Students in groups build, practise and video capture demonstrations.

15 mins – Bring the whole class together to share best video clips and ideas, and relate to what footballers do.

TEACHING POINTS

CAUTION: When students are carrying out the activity, organize the positions of the groups around the room in order to minimize problems of the spinners hitting other students. Check if any students have a latex allergy: if so, they should not touch the elastic bands.

An important idea for class discussion is that different ways of launching the spinner affect how it spins, and this affects how it moves through the air. It is important that students use the terminology consistently, so talking about spinning refers to the spinner spinning on its own axis, while bending or curving refers to the path it takes through the air.

Students can try either expanded polystyrene cups (white) or polythene cups (clear). The polystyrene cups may be slightly lighter and have greater friction, so they demonstrate backspin particularly well. Demonstrating topspin requires more skill to launch the spinner upside down. For sidespin, the spinner needs to be launched at an upwards angle so it doesn't fall to the ground before showing sideways movement. You could also increase the movement by putting some cling film over the ends of each cup. Sidespin is good for making a video since it can show the bend over a long distance.

Finally, students could judge the best examples of any video clips, and relate these to explaining what happens on the pitch. Their experiences of the movement of different types of ball such as beach balls, as well as balloons, could also lead to further interesting discussions and ideas.

ON THE PITCH

These ideas will be relevant when students practise the following on the pitch:

- Different ways of kicking across the ball to get spin.
- Exploring sidespin with the inside and outside of the foot.
- Exploring backspin and topspin and trying to kick it with no spin.

This part of the booklet provides further background on the physics underlying each of the sessions. Much of this goes beyond what is necessary for the students to be able to engage successfully with the ideas in the session. It aims to provide additional information for teachers and to suggest explanations which may be appropriately used in the classroom depending on the interests and achievement of the students. Further information about these physics concepts and how they can be taught to students can be found in the IOP Supporting Physics Teaching (SPT) materials on supportingphysicsteaching.net

PHYSICS EXPLANATIONS

SESSION 1

HOW CAN YOU KICK AND THROW A BALL FURTHER?

When a ball is thrown or kicked, it travels through the air, falling and then hitting the ground. The distance that a ball travels in the horizontal direction before it hits the ground (i.e. its horizontal displacement) is called the range.

The range of the ball depends on two things:

- the speed in the horizontal direction, called the horizontal velocity (velocity is the speed in a certain direction)
- the time of flight.

The formula that relates these is:

range (metres) = horizontal velocity (metres/second) x flight time (seconds)

If we kick the ball directly upwards it has a flight time and obviously travels a distance, but only in the vertical direction, so it has not gone anywhere in terms of horizontal displacement and the range is zero.

If the ball is kicked at a shallow angle, it has a high horizontal velocity but it quickly falls and hits the ground. It therefore has a very short time of flight, and so has a short range.

Somewhere between these two extremes is the angle that gives the greatest range. A simple model is to assume that the ball is kicked in a vacuum so that there is no air resistance. Calculations using equations of motion then predict the optimum angle to be 45° and that the flight is a symmetrical parabola.

Theory predicts that the optimum angle is 45° to give the maximum horizontal distance.

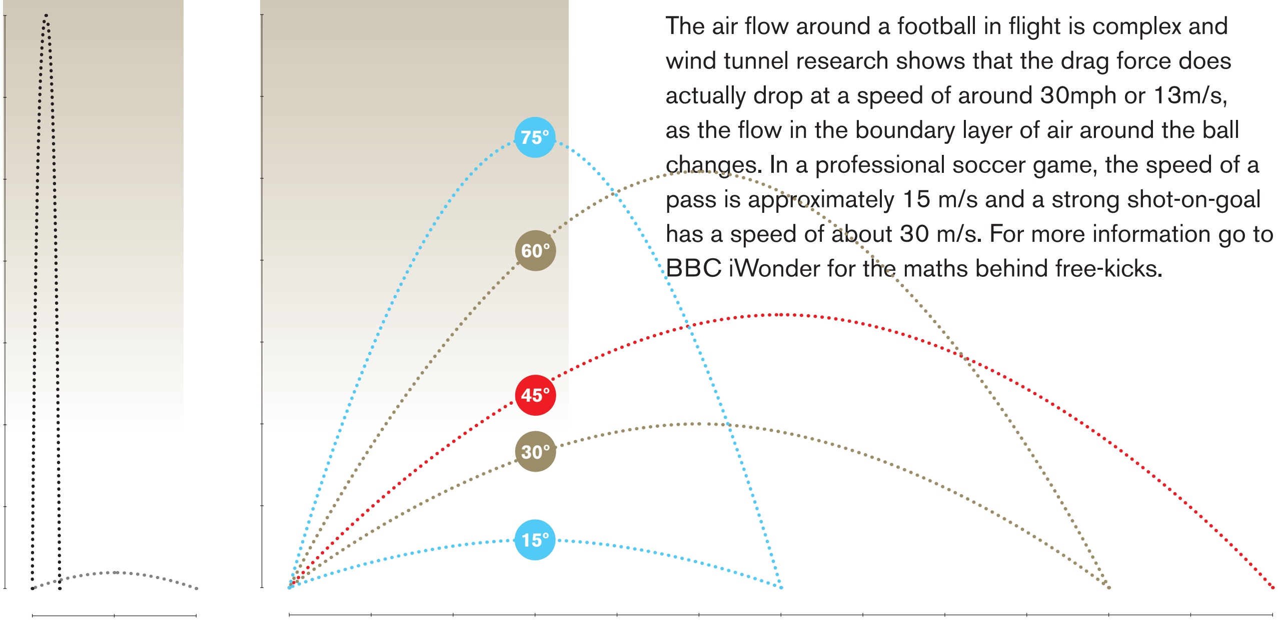
After being kicked or thrown, the ball is a projectile – an object that is travelling through the air and is not floating, gliding or flying by itself. The ball falls back to earth due to the force of gravity acting on it. For 45° to be the optimum angle, gravity has to be the only force acting on it (in this case, the object follows a path shaped like a parabola). Unfortunately life is never as simple as that and the ball will be slowed down by a force called drag that acts whenever an object moves through a fluid (fluids are gases and liquids). When travelling through air, this force is also called air resistance.

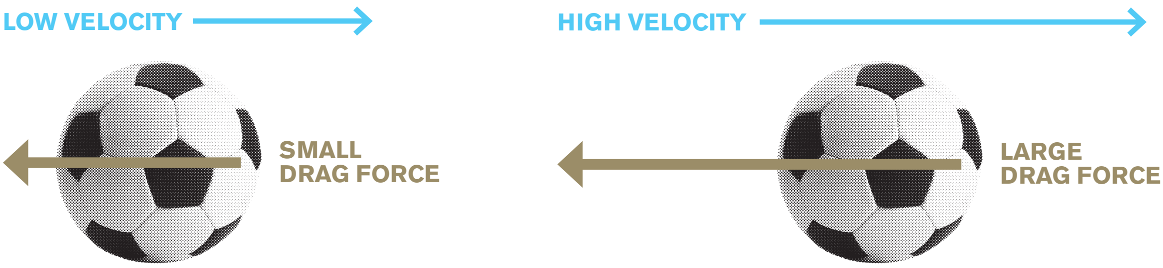
A football will have a greater drag force on it the faster it travels. Any cyclist will have experienced this, as going faster feels like going into a stronger headwind. It is the increase of this drag force with velocity that stops cyclists from going really fast.

The air flow around a football in flight is complex and wind tunnel research shows that the drag force does actually drop at a speed of around 30mph or 13m/s, as the flow in the boundary layer of air around the ball changes. In a professional soccer game, the speed of a pass is approximately 15 m/s and a strong shot-on-goal has a speed of about 30 m/s. For more information go to BBC iWonder for the maths behind free-kicks.

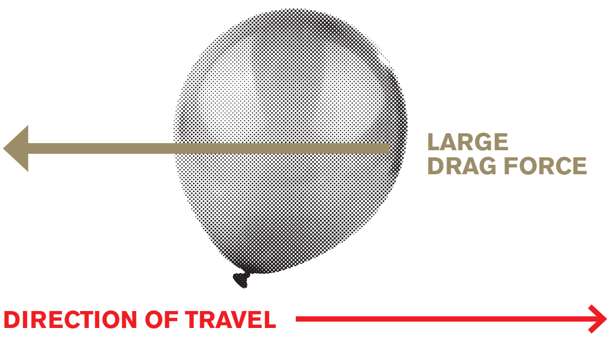
The ball does not travel far horizontally if it is launched directly upwards or at a very shallow angle.

Theory predicts that the optimum angle is 45° to give the maximum horizontal distance.





Showing the drag force on a ball for different velocities.



An uninflated balloon can be thrown further than an inflated one because of the difference in drag forces.

The importance of the effect depends on the surface area to mass ratio, and can been seen if you try throw a balloon a long way. You can throw an uninflated balloon further than an inflated one because of the large surface area of the inflated balloon compared to its mass. Footballs are not as extreme as this but the effect is still noticeable and so spoils the '45° theory'.

So what effect do drag forces have on the optimum angle for a kick or a throw? There is no simple answer to this, since the drag force varies depending on the velocity of the ball, and this will affect the angle. In addition, as football is played outside there is often a wind and this also needs to be taken into account.

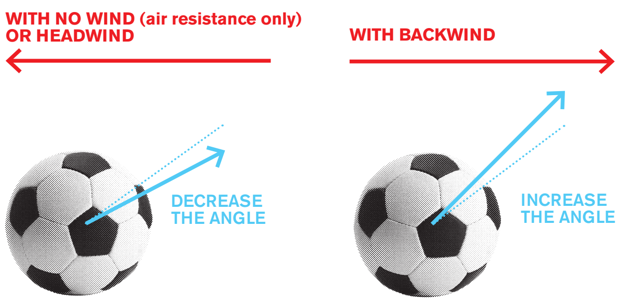
The effect of the air is to slow the ball down. So you need to kick the ball lower than 45° to give it a greater horizontal velocity and reduce the slowing effect of the air. This effect will be greater the faster you kick the ball. For small velocities, the optimum angle will approach the theoretical value of 45°.

If there is a headwind, this too has the effect of slowing the ball, so the angle should be less than 45°. Conversely, if there is a backwind you want the ball to be in the air longer and so the angle should be more than 45°. If you think about trying to make a feather go as far as possible with the wind you would throw it straight up in the air.

The optimum angle for a kick is affected by the presence of air and whether a wind is blowing.

In practice it is very difficult to kick the ball off the ground at angles around 45° which is why it is easier for a goalkeeper to pick it up with their hands if they want to kick it further. For the same reason, players sometimes flick the ball in the air with their foot before kicking it in the air. One interesting point is it is also easier to kick it a long way if the ball is rolling slowly towards you. This is because the ball rolls up onto your foot and so is in the right position to be kicked at a raised angle.

A final consideration is whether the ball is spinning or not. Backspin, topspin and sidespin affect the trajectory of a ball in different ways, and so will affect its range. This is discussed in more detail in Session 8.



SESSION 2

TAKING BETTER PENALTIES

There are two ways in which a penalty taker can fail to score: the shot can miss the goal or it can be saved by the goalkeeper. So, the probability of scoring is the product of the probability of the shot being on target at the goal and the probability of the goalkeeper not saving it.

These probabilities will be different depending on the area of the goal aimed at, and they will also be different depending on the particular player or goalkeeper. For some experienced professional penalty-takers, a good strategy is probably to aim at either top corner of the goal, since these shots are most difficult for a goalkeeper to save. However, for a less accomplished player, this might not be such an effective strategy, because of the higher probability of missing when they are aiming at the top corner.

The best strategy will therefore depend, amongst other things, on the accuracy of a player's shots. High accuracy means that the ball goes where it is aimed. This is related to the concept of accuracy in measurement, where an 'accurate measurement' is one which is close to the 'true value'. Usually in measurement, a number of readings is taken and an average is found, and this can improve the accuracy.

But in football, getting the average position of your penalty shots in the right place is not much use – each individual shot needs to be consistently in the right place. This idea also relates to another related concept in measurement – that of precision. High precision means that each shot consistently goes in the same place. A penalty-taker needs both high precision and high accuracy: having high precision but poor accuracy would mean that the shots consistently missed their target by the same amount.

It would seem, therefore, that any particular player could work out their own best place to shoot and each goalkeeper could work out their own best place to dive, and then to use this strategy every time. The difficulty is that when goalkeepers notice patterns in penalty-takers' strategies, they will modify their own strategy accordingly. And penalty-takers will modify their strategies depending on the known preferences of goalkeepers. In fact, the best strategy is to introduce a random element so that predictions are difficult to make about what the opposing player will do.

So, analysis of strategies for penalty taking is a classic example of game theory. It relies on understanding the strategy of your opponent, and modifying your own strategy accordingly – while recognising that they will be modifying their own strategy in the light of what they understand about yours. Psychology therefore plays an important part.

Goalkeepers play psychological games like dancing and waving their arms around. The rules state that a goalkeeper must be on their line but not where on the line, so they can move from side to side along it. By standing to one side of the goal they can try to make the taker go for the other side, and then dive that way.

Similarly, the penalty-taker can try to fool the goalkeeper about which way they will kick the ball. Pretending to take the shot is deemed to be unsporting behaviour and is penalised, but the penalty taker may 'stutter' or 'feint' in their run up hoping that the goalkeeper will dive the wrong way. However, according to a study at Exeter University, looking at the goalkeeper means that the penalty taker is more likely to miss.

Calculations based on the speed of the ball and the distance from the penalty spot to the goal show how little time the goalkeeper has to react to the ball. According to the Guinness Book of Records, the fastest football kick is 129 km/h (80.1 mph) achieved by Francisco Javier Galán Marín of Spain on 29 October 2001. This equates to 35.8 m/s. In reality the fastest kick is likely to be higher than this since this was measured in a studio. Typically a fast penalty kick would be around 30 m/s (67 mph). The distance to the goal from the penalty spot is 12 yards, or approximately 11 metres.The time taken for a ball at 30 m/s to reach the goal can be found using the formula:

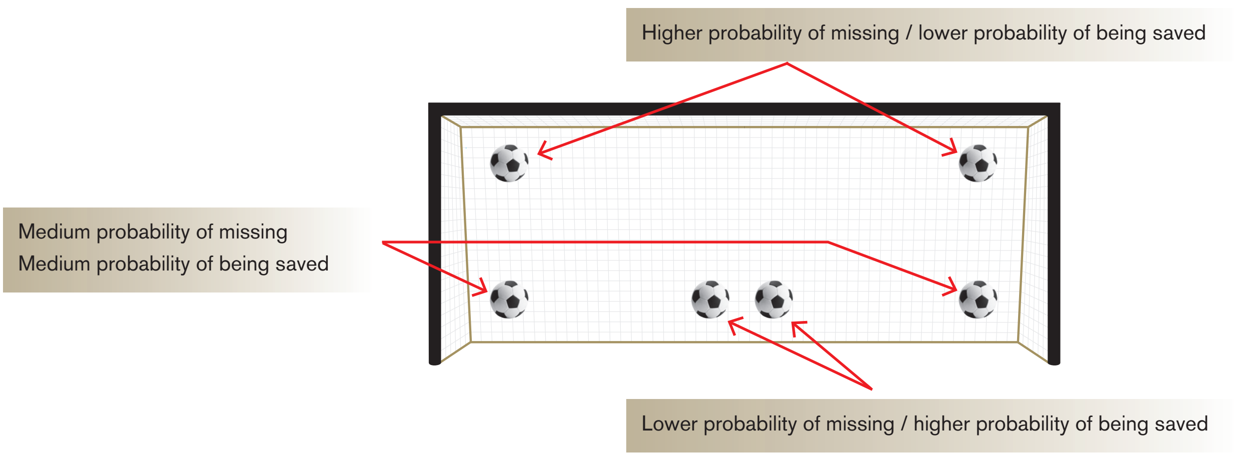
$$\text{time} = \frac{\text{distance}}{\text{speed}} = \frac{11\text{m}}{30\text{m/s}} = 0.37\text{s}$$

Reaction times can be found directly using a reaction timer (such as an app for a mobile phone), or indirectly by using the 'ruler drop test'. Using the following equation, the reaction time can be calculated from the distance the ruler falls before being caught:

$$\text{time} = \sqrt{2d/g}$$

Typical reaction times for this are around 0.2 s. However, in this test, the nerve signal needs only to travel from the brain to the fingers. A goalkeeper would need to send a signal further down the body to the legs in order to jump, so the reaction time would be longer. The 'thinking distance' for stopping a car travelling at 30 mph is given in the Highway Code as 30 feet – this corresponds to a reaction time of 0.68 s.

From these 'order of magnitude' estimates of the time for the ball to travel and for reaction times, the conclusion is that the goalkeeper has to decide before the ball is kicked where they think the ball will go and to move accordingly. Waiting until they can see which way the ball is moving would mean that a well-struck shot aimed at a top corner would score every time.



SESSION 3

HOW CAN YOU ACCELERATE FASTER?

In everyday language, there are various words that are used to describe the way that things move. In physics, these words can have different meanings, and it is important to understand the way that the terms are defined by scientists.

In describing the motion of a footballer some key terms are:

Distance

How far the footballer has travelled – how much ground they have covered (measured in metres, m).

Displacement

The distance from the point of origin – how far away they are from their starting point in a particular direction (measured in metres, m).

So consider a striker who starts in the centre circle to take the kick off from the centre spot. In the game he runs around a lot but if the opposition scores a goal, he goes back to the centre spot. He is now back where he started from so his displacement would be zero although he may have travelled a considerable distance.

Speed

The rate of change of distance – how fast someone is moving (measured in metres per second, m/s).

Velocity

The rate of change of displacement – how fast someone is moving in a particular direction (measured in metres per second, m/s).

Acceleration

The rate of change of velocity (measured in metres per second per second, m/s/s or m/s^2).

An athletics track provides a useful way of understanding the differences between distance and displacement, and between speed and velocity:

Distance and displacement

In a 100 metres race, the athletes will run a distance of 100 metres, and the displacement is also 100 metres (this is the distance of the end from the starting point). However, in a 400 metres race, the runners have travelled a distance of 400 metres, but have a displacement of zero as they are back to their starting point.

Speed and velocity

In a 100 metres race, the speed of the athletes increases even though they continue to travel in the same direction, so they are accelerating. In a 400 metres race, even if the athletes travel at the same speed around the bend, their direction is changing, so again, they are accelerating (towards the centre of the bend).

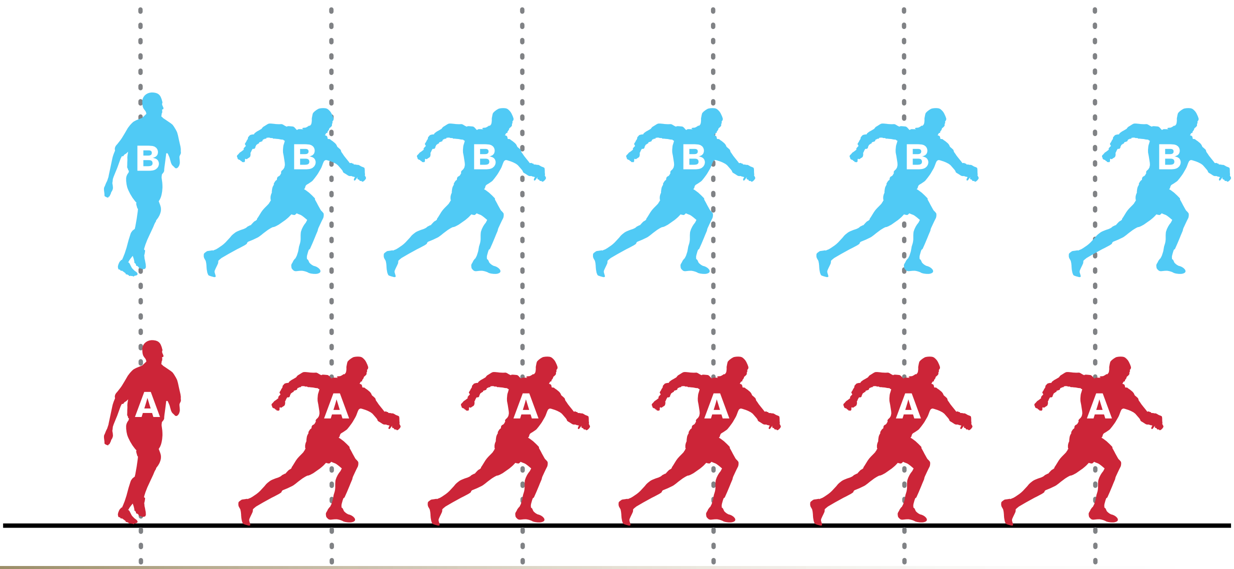
Acceleration

If the speed or the direction (or both) is changing then the athlete is accelerating.

The top speed of a footballer depends on two things: how quickly they can accelerate and for how long they accelerate. So, if there are two people starting a race from the same point then the one with the quicker acceleration will go into the lead, but if the other one accelerates for a longer time they may have a higher top speed and catch up and overtake the leader.

For the majority of the cases in football it is explosive acceleration that is the most useful, being able to get to the ball first over a short distance. A higher top speed becomes important when the chase for the ball is longer in situations such as a counter attack on the break, or a long ball knocked over the top of a defence for the attacker to run on to.

Observing a sprinter such as Usain Bolt, you can see that he runs in a very upright fashion with a high centre of mass and a long stride length, which does not make changing direction easy at all. Theo Walcott, by comparison, runs on his toes with a much shorter stride. He keeps a low centre of mass enabling him to change his direction quickly while keeping his balance. (Body position and balance are considered in more detail in Session 7.)

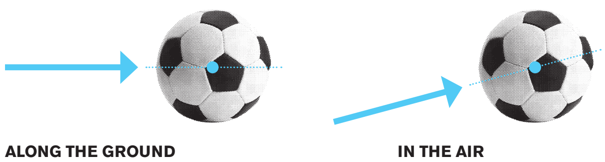


Player A accelerates faster than player B so goes into the lead.
Player B however accelerates for longer and so catches up and overtakes player A.

SESSION 4

WHAT MAKES A GOOD PASS?

Moving a ball by kicking it requires a force to be exerted on the ball by the foot. The direction of the force will determine whether the ball travels along the ground or in the air. By kicking through the centre of mass (or centre of gravity – the point at which the whole weight seems to act), the ball won't spin.



A horizontal kick through the centre of mass will make the ball travel along the ground. To make the ball travel in the air, the kick needs to be at an angle to the ground.

A beanbag is a convenient and simple way of modeling a football. It avoids the more complex aspects of a football's behavior (spinning in the air and rolling along the ground) and focuses only on the displacement. (Spinning will be looked at in Session 8, and will require a different way of modeling the ball.)

It should be clear that, over short distances, a beanbag can be passed faster along the floor than in the air. If it is thrown as fast from floor level to floor level, it will travel further and won't land at the player's feet. It should also be clear that there is a limit to the distance for sliding the beanbag due to the friction between the beanbag and the floor. At some point, the beanbag would either never get to the other player or be slower than the beanbag that is thrown.

So, a pass on the ground can get to a player's feet (where it is easier to control) more quickly than one in the air. This idea may not be obvious. Of course, there are limits and these depend on how fast the player can kick the ball to start with and the surface of the football pitch. On a really good pitch, the players can kick the ball very hard and the pitch is relatively smooth and usually watered, so there is less friction and the ball can skid (slide) quite a way before clearly starting to roll. A football will travel further along a smooth hard surface like Astroturf or an indoor court, but less far along a rough bumpier surface such as long grass, muddy grass or sand.

A force diagram is a representation that shows all the forces acting on an object. Using these can help students to understand the various forces acting on a ball as it is kicked, and accelerates and decelerates during a pass.

The diagrams opposite show the forces acting on a beanbag in two situations – slid along the floor and thrown in the air. Each set of diagrams shows three stages of its movement. The conventions used here are:

The object is shown as a point (since the forces can be modelled as going through the centre of mass and the object spinning can be ignored).

Only the forces acting on the object are shown.

The tails of the forces are shown touching the object (since there is often more than one force acting on an object, and otherwise the diagram can get messy with overlapping arrows).

The relevant forces involved when a beanbag is slid or thrown are:

Weight
The weight of the beanbag acts downwards because of the gravitational pull of the Earth on the beanbag.

Support
This is the force of the floor on the beanbag and acts in the opposite direction to the weight of the beanbag.

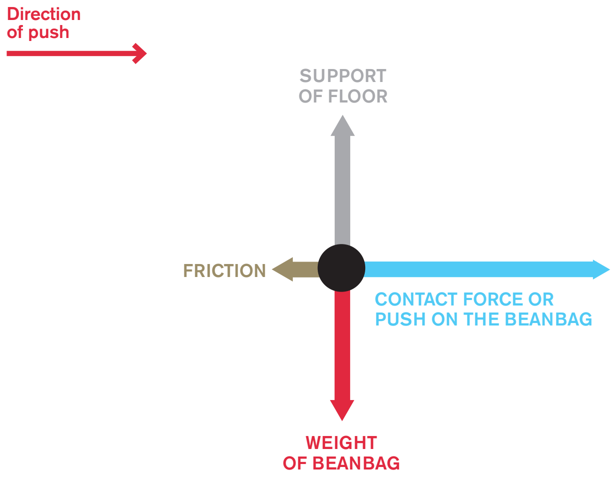
Contact force
This is force of the hand on the beanbag as it is thrown.

Friction
When objects move against each other, the surfaces in contact resist the motion. Friction always acts in the opposite direction to the motion of the object.

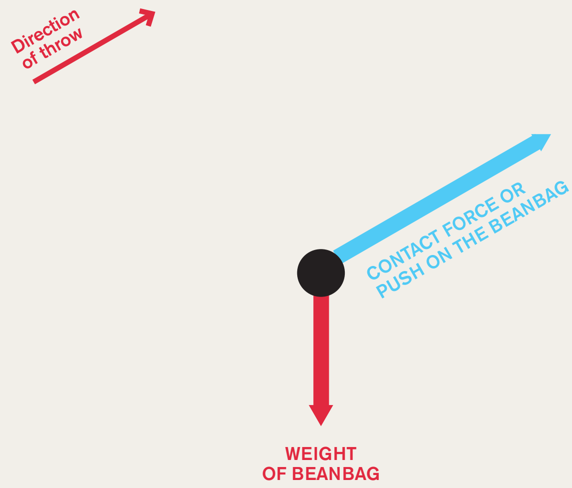
Drag (or air resistance)
When an object moves through air, it is slowed down by the air. Like friction, drag always acts in the opposite direction to the motion of the object.

It is a common misconception amongst students that an object needs a force to keep it going. They need to understand that the force of the throw is only there when the hand is in contact with the beanbag. Once the beanbag has left the hand, this force is no longer there – the beanbag doesn't need a force to keep it going (Newton's First Law).

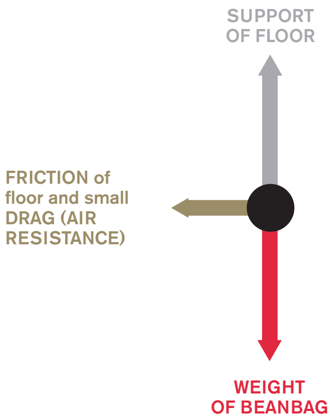
BEANBAG BEING PUSHED ALONG THE FLOOR



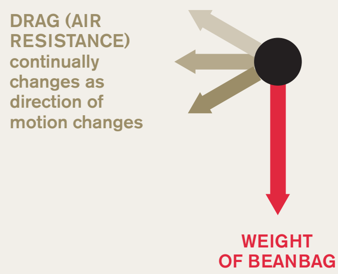
BEANBAG BEING THROWN IN THE AIR



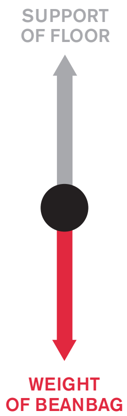
BEANBAG SLIDING ALONG FLOOR (AFTER PUSH)



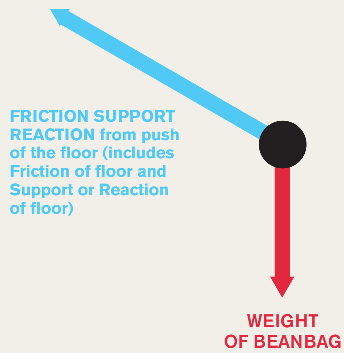
BEANBAG IN AIR (AFTER THROW)



BEANBAG HAS COME TO A STOP



BEANBAG HITTING GROUND



SESSION 5

FORCEFUL TACKLING

The effect of an impact force depends on the area over which it is applied. We intuitively know this from our everyday experiences. Our front teeth are sharp to chop our food, while our feet spread our weight over a greater area. So spreading out forces avoids causing damage, while concentrating a force over a small area can pierce things.

The idea of forces being applied over different areas and the effects of this are often put under the heading of 'pressure'. However, it is really helpful for students to be able to distinguish between pressure in liquids and gases (or fluids more generally) and pressure acting on solids (which is called stress). The processes are very different: pressure in liquids and gases requires that the particles can flow, whereas this is not the case in solids. Rather than referring to pressure when talking about solids, it is helpful to use an adapted formula:

$$\text{stress (on solid)} = \frac{\text{force (on solid)}}{\text{area over which force is applied}}$$

This formula could be used to give an explanation of why reducing the area over which the force is applied gives a greater stress (or 'pressure') on the solid, and the reason for the deeper indents in the play dough in the practical activity.

However, what the practical activity is modelling is an impact (the kick of a boot on another player's leg, for example) rather than the application of a constant force in a static situation. It might be useful to think about this in terms of how long it takes to bring an object to a halt. This is related to Newton's Second Law of motion, which is usually expressed as:

$$\text{force} = \text{mass x acceleration}$$
$$(\text{or } F = ma)$$

This can be rearranged to:

$$\text{acceleration} = \frac{\text{force}}{\text{mass}}$$

In the practical activity, the falling ball slows down (decelerates) when it hits the Lego brick, so in this case the acceleration is negative (the force is acting in the opposite direction to the motion of the weight).

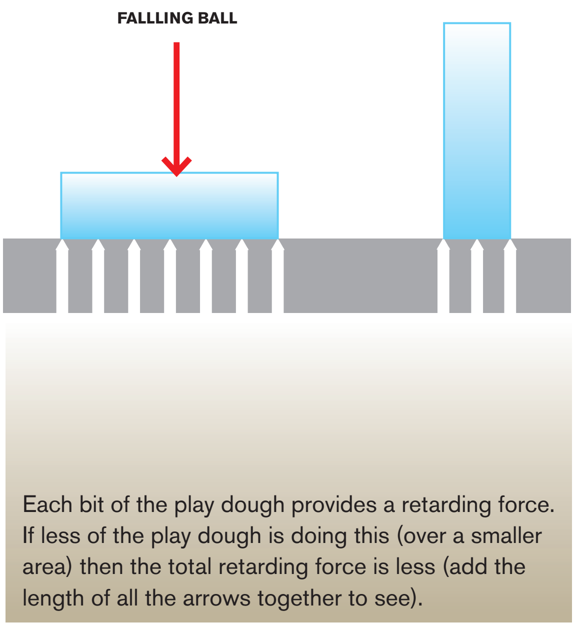
The size of the retarding force acting on the mass of the Lego brick and heavy ball will depend on the contact area. With a greater area, the retarding force is greater, and the ball will slow down more quickly (greater negative acceleration). Because it comes to a stop more quickly, the indent in the play dough is less. Conversely, if the Lego brick is placed upright, with a small contact area, it will take longer to slow down and stop: the indent, and hence damage, will be greater. By orienting the Lego brick so that the studs are face down a particularly powerful image results.

Applying this explanation to a football tackle, how quickly an incoming boot or stud slows down depends on the size of the contact area. A reduced area means less retarding force is applied by the part of the body being hit, and so the incoming boot keeps going for longer and therefore deeper. This is what causes the damage. So a 'studs up' tackle is far more dangerous than from a flatter part of the boot. By using shin pads, the force is spread over a much greater area. This means that a greater retarding force slows down the incoming boot much quicker, while the force on the shin is spread over a much greater area.

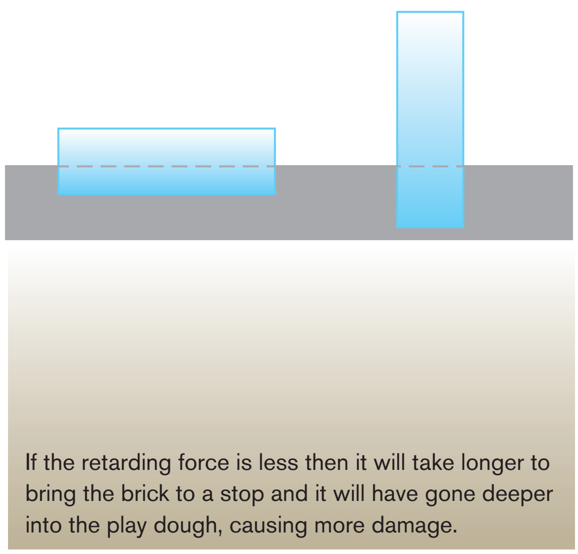
The worse-case scenario is the two-footed, studs-up tackle with both feet off the ground. Here a much greater force is required to stop the entire mass of the player (in the equation $F = ma$, the value of m is the mass of the player rather than just the mass of their boot, foot and leg). So, the only thing stopping the motion (or momentum) of the tackling player is the other player's leg or ankle.

The amount of damage done can be thought about as how long it takes to stop the impacting object.

AT IMPACT



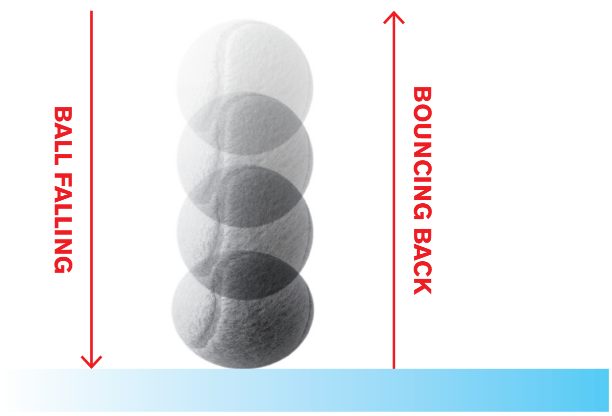
AFTER IMPACT



SESSION 6

HOW CAN YOU CONTROL A BALL EFFECTIVELY?

When a falling ball makes contact with the ground it starts to deform and it decelerates until a point is reached when it stops moving. Then it starts to elongate and it accelerates away from the ground. In a way, it is a bit like an object thrown into the air which reaches its highest point and then starts to fall again. As it rises, it decelerates, then it stops moving as it reaches its highest point, and then accelerates towards the ground.



A falling ball deforms and decelerates as it makes contact with the ground, and then accelerates upwards.

Using the words deceleration as well as acceleration is a natural way of speaking, but in physics only acceleration is used as a quantity. It is a vector quantity meaning that it has both a magnitude and a direction. The ball experiences the same acceleration due to gravity (9.8 m/s^2 downwards) whether it is rising or falling. For a falling ball the acceleration is in the same direction as the motion and the ball speeds up. For a rising ball the direction of motion and the acceleration are in opposing directions and the ball slows down.

Similarly, a bouncing ball is subject to an upward acceleration as it is deforming and slowing down, as well as an upward acceleration as it starts to elongate and speed up. What makes this situation much more complicated than a ball thrown in the air is that the acceleration changes during the period of the bounce, and, because the ball deforms, the acceleration at different points within the ball are different from each other.

Understanding the detailed mechanisms involved in bouncing can get very complicated. But a simple way of gaining insight into what happens during a bounce, and in particular why some things bounce better than others, is to think about it in terms of energy.

In a perfectly elastic collision, the ball travels with the same speed but in the opposite direction after the collision. It has the same amount of kinetic energy after the collision as before it. Real collisions however are not like this. The speed of the ball before the bounce is greater than the speed afterwards. This means it has less energy. Since energy is conserved, it cannot just disappear. So, where has the energy gone?

When a ball is travelling towards a surface, all of the particles of the ball (atoms / molecules) are travelling in the same direction. When it hits the surface, both the ball and the surface will deform, and this makes the particles vibrate or 'jiggle' a little more. When the ball bounces it moves away more slowly. So, some of the 'organised motion' of the particles in the ball has been lost, but the random or irregular motion of the particles in the ball and the ground has increased. This increase in the irregular motion or 'jiggling' of the particles is what we observe as an increase in temperature. One way of talking about this is to say that energy has moved from the kinetic store (which we observe as the movement of the ball) to the thermal store (which we observe as the temperature of the ball and the ground). Since energy is conserved, whatever amount of energy comes out of the kinetic store is what goes into the thermal store.

It is possible to make calculations on these amounts. A football has a mass of about 0.45 kg and when kicked hard can travel at about 30 m/s. Using the formula for calculating kinetic energy ($\frac{1}{2}mv^2$) this gives a value of about 200 J. If this ball hit a player and stopped completely, then a lot of the energy would be transferred to the player. To get an idea about magnitudes, suppose this energy was used to raise the temperature of some water, say one litre, the rise would be about 0.05°C (using the formula for thermal energy, mc). This is a barely detectable rise in temperature. When the energy spreads out into the surroundings, the temperature change will be even smaller, and this is why we have a tendency for thinking about energy as being 'lost'.

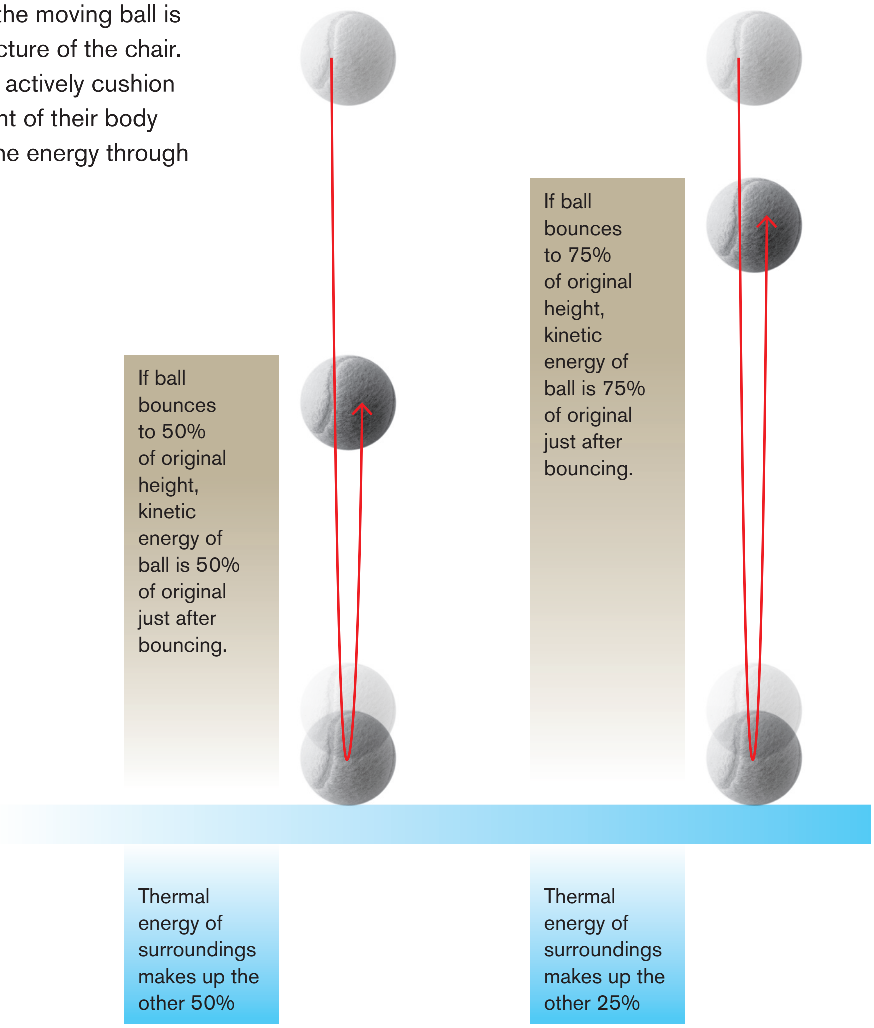
How well something bounces depends on the materials that the object and surface are made from. If the particles are able to be squashed together and return to their original positions with the minimum of additional 'jiggling', then the object will bounce well. If a lot of the organised motion of the particles ends up in making them jiggle, then the object won't bounce well.

For example, on a concrete surface a tennis ball bounces well but a ball of Plasticine does not. The particles in the tennis ball are good at getting squashed together and then regaining their original positions, but the particles in the Plasticine are not. As a result, the Plasticine will warm up more than the tennis ball. Similarly, a tennis ball bounces better on concrete than on mud. Mud is not good at regaining its shape when deformed, and the bounce will warm it up more than the concrete.

The other factor explored in the practical activity was the effect of the rigidity of the structure. The principle is similar to the effect of the nature of the material from which an object is made. The ball does not bounce well off mud, because this is not a very elastic material, and a large proportion of energy is dissipated through it during a bounce. Similarly, a ball does not bounce well off a wobbly chair, because the energy of the moving ball is dissipated throughout the whole structure of the chair. This is what footballers do when they actively cushion the ball – they are using the movement of their body as the ball strikes them to dissipate the energy through their body.

Skilled footballers instinctively use these two factors in combination. From a scientific perspective, they are closely related. Things don't bounce well from a wobbly chair because the structure of this arrangement is such that energy is readily dissipated through the chair. Similarly, things don't bounce well from mud because at a molecular level it is also a structure that dissipates energy – the arrangement of particles is such that when deformed energy tends to spread through the material making it a little warmer.

Slowing a ball down or making it change direction involves changing its momentum. Heavy, fast-moving objects have high momentum and light, slow-moving objects have low momentum (momentum = mass x velocity). The impact that this has on the body also depends on how quickly the momentum is changed. Slowing a ball with the chest happens over a longer time than heading a ball, which involves a rapid change in momentum and produces a large force on the head. Heading safely is important. The bone behind the forehead is very thick and able to withstand a large force whereas the bones at the side of the head, the temple, are much thinner and offer much less protection.



When a ball bounces, some of the energy spreads out is transferred to the surroundings.

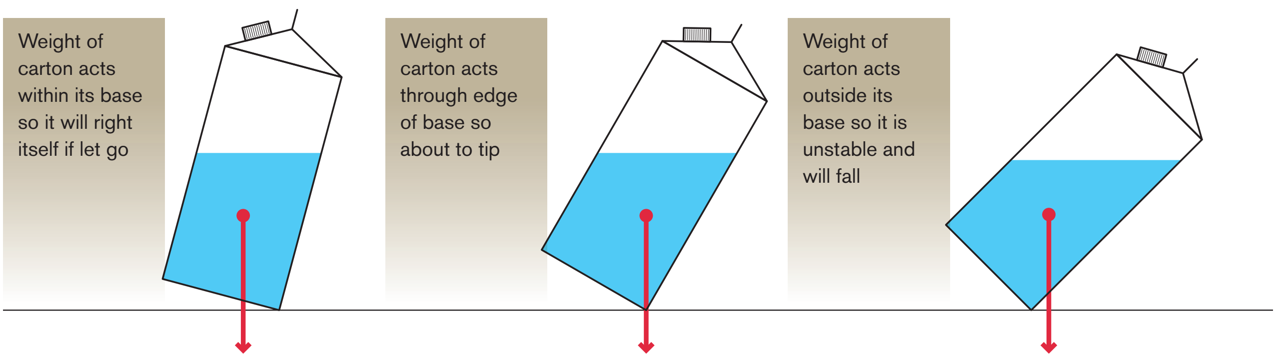
SESSION 7

USING YOUR BODY FOR BALANCE AND STABILITY

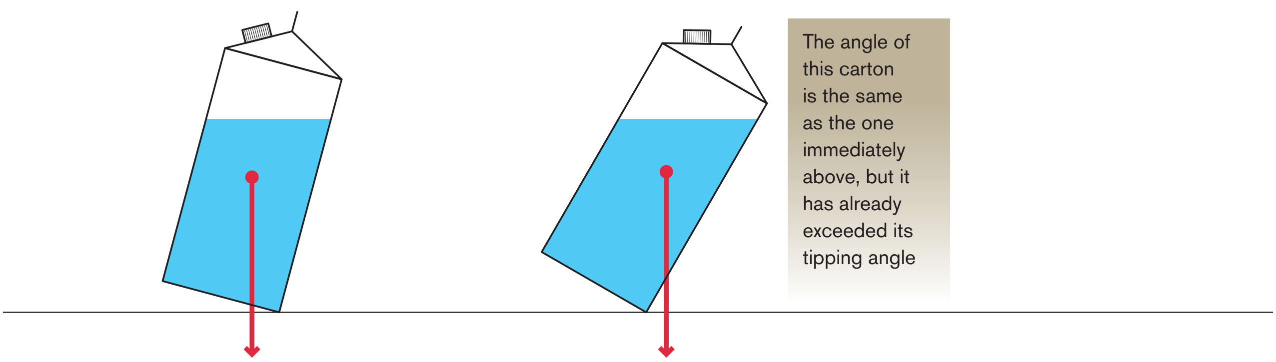
Balance and stability are both relevant to the way footballers control the position of their bodies, but the two concepts are rather different. Stability is concerned with how hard it is to topple something over. For example, a cup of tea is more stable than a pencil standing on end – the pencil only needs a slight push to knock it over. Balance is more dynamic, and is concerned with the way moving things can maintain a position. For example it is easier to walk on a tightrope if your arms are out to the sides or you are carrying a long pole.

How stable an object is depends on how its mass is distributed throughout the object rather than just its mass.

Tipping a carton with a lower centre of mass. Once the centre of mass is outside of the base, the carton will tip over and fall.



Tipping a carton with a higher centre of mass.



Stability and the tipping carton: The weight of an object can be treated as acting through its centre of mass, and an object is stable if the centre of mass lies above the base. If it is not above the base then the object will topple. Objects with a wider base will therefore tend to be more stable than those with a narrower base. In the practical activity, the carton has a fixed sized base, and the general rule is that the greater the amount of water, the smaller the tipping angle. This is because the centre of mass is higher when there is more water. So, when it comes to being stable, it is not how much mass something has, but how this mass is distributed.

Because the centre of mass of the carton is higher when there is more water in it, as soon as you start to tip it, more of that mass goes beyond the base, making it less stable. It will therefore reach its tipping point at a smaller angle from the upright, compared to when there is less water and the centre of mass is lower.

Although the general result is that less water in the carton means a smaller tipping angle, it can come as a surprise that an empty carton seems to be an exception to this rule. An empty carton tips at about the same angle as a full one, and both tip at a smaller angle than a carton that is half filled with water. This emphasises the idea that it is not the mass of the object which is the relevant factor as the cartons clearly have different masses. However, both the empty and full cartons can be treated as having their mass symmetrically spread out over the whole object, and so their centres of mass are in the same position.

This suggests that for two players of the same height, the heavier one would be just as stable provided their masses were spread out in roughly the same way. However, two players of the same height and weight might differ in stability. For example, if one had very broad shoulders and the other had particularly muscled legs, then the latter one should on average be more stable.

One might think that all else being equal, a taller player would become unbalanced at less of an angle from the upright. However, other factors are usually not equal. For example, taller players tend to have slightly larger feet, and they stand with them slightly further apart, thereby providing a wider base. More importantly, players actively move their bodies.

Balance and the ‘weighted rule’: When you walk, for most of the time your centre of mass is not directly about your feet. Your centre of mass moves forward over your foot, and the other foot moves to the front to stop you tipping over. On a tight rope you would also have to stop yourself from falling to either side. Raising your arms or holding a pole make your centre of mass higher, so it seems counter-intuitive that this could help you balance. Balancing a metre rule is easier when a weight it attached to the top rather than the bottom of the rule, and this illustrates the same effect.

There are two main reasons that it is easier to actively balance the metre rule with a higher centre of mass. Both of these reasons emphasise the dynamic nature of the way we continually make adjustments using our muscles to keep the rule balanced.

The first is that when it pivots at its base, it rotates and falls faster when the centre of mass is closer to the pivoted end. In effect, the centre of mass has less distance to fall if it is closer to the base. You therefore have less time to react. The second reason is that when the metre rule has the weight at the top, it is tolerant of very large movements of your hand. When the weight is at the bottom, it is very sensitive as it magnifies small movements into large changes.

The combination of these effects means that when the centre of mass is low, the metre rule is already at a greater angle and falling faster when you start to feel it is tipping. You need to respond quickly, and because of the sensitivity to movement, you are likely to ‘overshoot’. It needs a series of rapid and precise corrections to keep the rule balanced. In contrast, when the weight is near the top you have more time to react, and the adjustments to the rule can be made more finely.

The key idea here related to football is that players are not static objects but actively control their bodies. Although having a higher centre of mass means that a tipping point will be reached with a smaller angle, an active person can sense and hence correct the situation earlier. Different body shapes lend themselves to particular types of movement, but developing appropriate techniques through coaching and practice can have dramatic effects on player performance.

SESSION 8

HOW CAN YOU SPIN AND BEND THE BALL?

Objects that are thrown, kicked or otherwise launched will move through the air with an approximately parabolic path if the main force acting on them is gravity. (See Session 1, which discusses the movement of a projectile.)

However, the air will always have some effect on motion, and in particular objects will deviate from a parabolic path if:

- they are comparatively light for their size (low-density) such as a balloon: these are more subject to forces of buoyancy or upthrust, and drag or air resistance
- they are shaped in ways that will make them glide or are otherwise significantly asymmetrical, such as being flat or wing-shaped (these are subject to forces of lift)
- they are spinning while moving through the air, particularly if they are spherical or cylindrical: these are subject to forces arising from the Magnus effect.

When footballers spin and bend the ball, they are exploiting the Magnus effect. A spinning ball moving through the air experiences a force at right-angles to the direction of motion. The ball will therefore deviate from the path of a ball kicked with no spin.

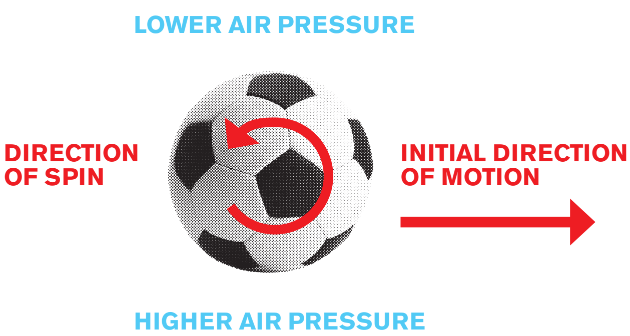
When a ball travels through the air, and it is not spinning, then all parts of the ball move with the same speed. However, if it is spinning, different parts of the ball are moving at different speeds.

In the case of backspin, the direction of spin means that the lower surface of the ball travels more quickly through the air than the upper surface. Friction between the ball and the air sweeps the oncoming air on one side around the back of the ball, causing the air on the lower side to get squashed up (increased pressure) while air on the upper side gets less squashed (reduced pressure). Since there is a difference in the air pressure between the top and the bottom of the ball, there is a force on it at right angles to its motion. The air pressure is greater at the bottom than the top, and so there is a net upwards force on the ball.

So the backspin creates a kind of lift which forces the ball upwards, in the opposite direction to the effect of gravity downwards. However air resistance is also acting and this slows down the speed of the spinning, thus reducing the Magnus effect. Footballers can use backspin to make the ball go as straight as possible with a flatter trajectory.

The opposite happens when topspin is imparted and the net force from the difference in air pressure is downwards. Similarly, sidespin will cause a difference in air pressure on either side causing the spinner to move sideways. Footballers can also use topspin or sidespin in a free kick to make a ball go over or around a wall of players and into the goal.

The general rule could be expressed as "the ball will move in the direction away from the side of the ball that is moving in the direction of motion."



Ball with backspin moving through the air will experience a net upwards force due to the difference in air pressure on the upper and lower sides.

NOTES

NOTES

For further information contact:

IOP Institute of Physics

76 Portland Place, London W1B 1NT
Tel +44 (0)20 7470 4800
E-mail education@iop.org
www.iop.org/education

Charity registration number 293851
Scottish Charity Register number SCO40092

This resource is available to download from our website **(www.iop.org/football)** and if you require an alternative format please contact us to discuss your requirements.

Published: 2014 Stock code: EDU001

The Kitemark is a symbol of certification by BSI and has been awarded to the Institute of Physics for exceptional practice in environmental management systems.

Certificate number: EMS 573735