Flying Start Challenge

Drag Activity

A brief introduction to drag

Activity Details

This activity will explain

- Forces on a falling body
- Newton's laws
- What drag is
- What impact drag has on an object
- What factors impact the amount of drag on an object
- You will predict which object will hit the floor first when thrown from a plane then investigate how drag affects how quickly objects fall
- Once you have made your prediction you will work through the activity and calculate the correct order
- The final activity will be to create a parachute for an egg by applying your knowledge to win prizes

Prediction

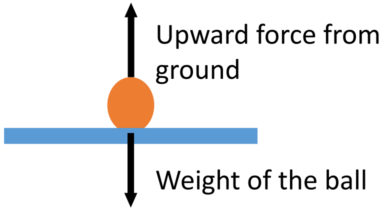
If all of the following objects were dropped out of a plane at 10km (roughly how high passenger planes fly) in what order would they hit the floor?

- A golf ball
- A bowling ball
- An elephant
- The Eiffel Tower
- A brick
- A person
- A hammer
- A feather

You are not expected to know the answer to this so don’t worry if you have no idea

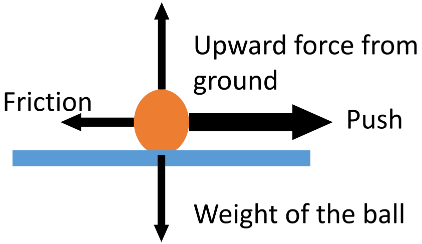
Newton's 1st Law

Sir Isaac Newton first published his famous laws in 1687. His first law states that an object will stay at constant velocity unless it is acted upon by an external force. (NOTE: At rest is a constant velocity of 0) This is very useful as it is equivalent to saying that if there is no overall force on an object (ie. if all the forces are equal), then the velocity is constant.



Consider the forces on a stationary ball on the floor:
The forces acting upon it are all equal to each other, this is known as being in equilibrium. What do we know about this ball's velocity?

If the ball was given a push horizontally, the new force diagram, at the moment it was pushed, would be:
As the forces on the ball are no longer equal, what can we say about its velocity?



Newton's 2nd and 3rd Law

We've already covered Newton's 1st law, but Newton's 3rd law is one that is commonly heard in the form:

"Every action has an equal and opposite reaction".

Whilst this is a simplification of the law, it sums it up well. The third law states that all forces between two objects exist in equal magnitude and opposite direction. ie. if we take our ball on the ground from earlier, the ball's weight acts as a downward force on the ground and the ground exerts an *equal and opposite* force on the ball.

This 2nd law can be simplified to the equation

$$F=m*a$$

This equation is used as a foundation for many engineering applications from rocket engine design, right through to building skyscrapers. Simply put, **the force on an object is equal to the mass of the object multiplied by the acceleration it is experiencing.**

Weight and Gravity

Gravity is something that acts between all objects with energy and pulls them together.

The gravitational force is calculated using the equation $F = \frac{GMm}{r^2}$ where G is a constant, M and m are the masses of the two objects and r is the distance between them. On Earth, the acceleration due to gravity is about 10m/s/s which I'm sure you've all seen in science lessons.

To calculate this, let's consider the gravitational force $F = \frac{GMm}{r^2}$. We also know thanks to Newton's 3rd Law that F=ma. Therefore, $F = \frac{GMm}{r^2}$ $= ma$. As you can see we have m on both sides of the equation so they cancel out leaving $= a$ $F = \frac{GMm}{r^2}$

If we plug the numbers for Earth into this equation: radius = 6371000, mass = 5.97x10^{24} and the constant G = 6.67x10^{-11}, the equation will look like.

$$F = \frac{6.67 \times 10^{-11} \times 5.94 \times 10^{24}}{6371000^2} = 9.8 = a$$

This value is the number you commonly see as the acceleration due to gravity (g) and means that we can simply use F=mg when wanting to know the gravitational force on an object which is close to Earth's surface.

This is also known as weight (W). If we use g as the acceleration in: $F = m \times a$, we get:

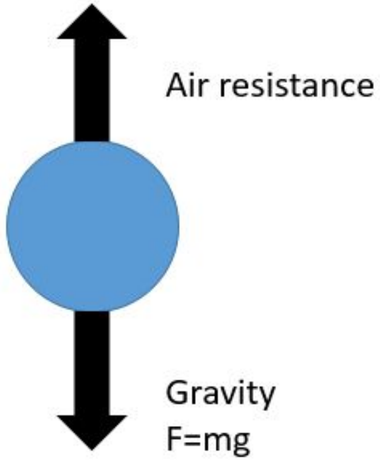
$$Force = mass \times gravity$$
$$F = m \times g \ \ and \ \ W = m \times g$$

Forces on a falling body

On a falling body the main forces are gravity and air resistance.

As Newton's 2nd law states F=m*a, hence the force of gravity acting on the object is the mass of the object x the acceleration due to gravity (10 m/s/s)

However the drag force is a bit more tricky to work out and that is what this activity will look at



What is Drag?

- Drag is a force that acts against an object's motion to slow it down
- It is generated when a fluid (a fluid is a liquid or gas) hits a solid object such as the surface of a car or plane.
- Benefits of reducing drag include: a higher top speed, better fuel efficiency and reduced wear on the surface.
- However it is sometimes a good thing to increase drag when you want to slow something down, as with a parachute.

What determines the amount of Drag?

As we learnt in the last slide, drag is caused by a fluid hitting a solid surface. It can therefore be assumed that properties of the fluid and properties of the surface impact the amount of drag.

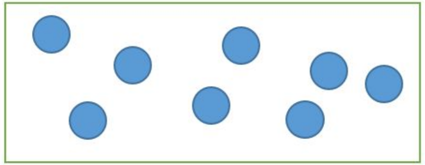
Fluid Properties

You can think of a fluid as lots of particles all floating around, and we know that the drag force is caused by a fluid hitting a surface

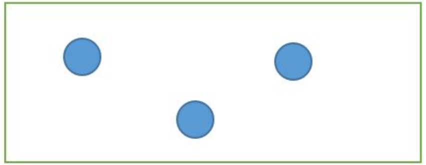
It would therefore be expected that the more fluid particles hitting the surface, the more force that will be created.

One way of increasing the number of particles hitting the surface is to squeeze more into a given space – this is known as the density of the fluid

Therefore, a higher density (more particles in a volume) will cause a higher drag force



High density



Low density

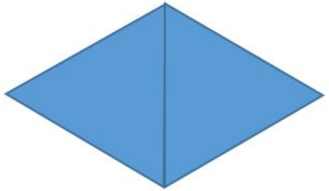
Object Properties

Another way of making more air particles hit the surface is by increasing the area of that surface. A larger surface area will therefore also increase the drag force on the object

Increasing the speed of the object moving through the air will also cause more particles to hit the surface. However, increasing the speed will also mean that the particles will hit the surface harder, creating a larger force. This means that speed impacts the force twice so must be included twice in the final equation.

The final thing is the drag coefficient. This is just a number that says how well an object moves through the air. A streamlined object would have a low drag coefficient but a something like a brick would have a high one. It is determined by the shape of the object.

High drag coefficient



Low drag coefficient

The Drag Equation

Putting the fluid properties and the object properties together we can see what affects the drag force.

Fluid density (ϱ)

Object speed (remember this has two impacts so needs to be included twice) (v)

Object surface are hitting the fluid (A)

Object drag coefficient (C_d)

$$F = \frac{1}{2}\rho v^2 C_d A$$

This equation is what we have just worked out (the ½ is just another constant).

We will use this equation to find out which object will hit the ground first

The Drag Equation

Now that we have made the drag equation, we can use it to determine which objects fall quickest and hence hit the ground first.

This will require rearranging the equation so that we can find the speed (v), but this isn't as difficult as it looks.

We start with the equation we worked out which tells you the force (F)

$$F = \frac{1}{2}\rho v^2 C_d A$$

We want to get v on its own so will first multiply both sides of the equation by 2

$$2F = \rho v^2 C_d A$$

We now need to divide by $\rho C_d A$ so that we are left with just v^2

$$\frac{2F}{\rho C_d A} = v^2$$

Finally we must square root both sides so that we are left with just v

$$\sqrt{\frac{2F}{\rho C_d A}} = v$$

Terminal Velocity

We now have an equation to tell us how fast an object can fall. This maximum speed is called terminal velocity.

Terminal velocity is the maximum speed an object can travel and occurs when the force causing the motion is equal to the drag force slowing you down

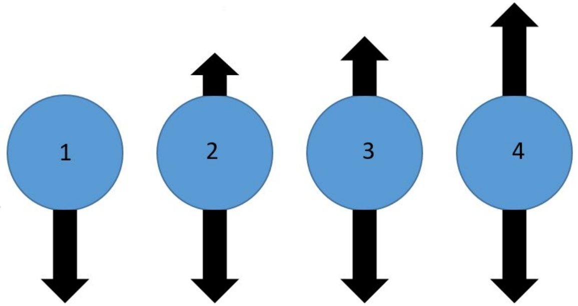
This is because drag is in the opposite direction to the force causing you to move, and as these forces are equal, they cancel out resulting in no overall force acting on the object (remember Newton's 1st law on slide 4). This means the object will travel at a constant velocity.

We will look at terminal velocity in more detail on the next slide and show an example.

Terminal Velocity

Consider a falling ball shown below where the numbers show different stages through its fall. (NOTE: The force due to gravity is always the same as F=ma where a=10m/s/s and the mass doesn't change)

1. The ball has just been dropped. Its velocity is 0 and hence the drag is also 0 (Remember that the drag force is $F = \frac{1}{2}\rho v^2 C_d A$ so if v=0 then the force is also 0.
2. The ball has had time to fall and gain speed. This means that v is no longer 0 so there is now a small drag force.
3. Its velocity has increased further and therefore so has the drag force.
4. The ball has reached a velocity such that the drag force is now equal to the force from gravity. This means there is no overall force acting on the ball. Using Newton's 1st law this means that the ball must now travel at a constant velocity (acceleration = 0).



The Drag Equation

The final question we need an answer to now is what is F?

This is actually quite simple now we know the object has reached terminal velocity. Remember that at terminal velocity the drag force is equal to the force causing you to move.

For our example of objects falling due to gravity, the force causing you to move is the force pulling you down – Gravity.

The force due to gravity is simply mass of the object x acceleration:

$$F = ma$$

This means that our final equation is:

$$v = \sqrt{\frac{2ma}{\rho C_d A}}$$

The Drag Equation

$$v = \sqrt{\frac{2ma}{\rho C_d A}}$$

To find which object hits the ground first we now just need to plug in the numbers. The table below contains all the values for each object. The average density between 10km and sea level is used.

Average air density (ϱ) = 0.82 Kg /m^3

Acceleration due to gravity (a) = 10 m/s/s

Object	Mass (m) Kg	Surface Area (A) m^2	Drag Coefficient (Cd)
Golf ball	0.046	0.0014	0.4
Bowling ball	5	0.036	0.47
Elephant	4000	9m	0.8
Brick	2.5	0.022	1.15
Person	80	0.8	1.2
Eiffel Tower	9,000,000	750	1.9
Hammer	3	0.015	1.2
Feather	0.000008	0.001	2.0

Example Calculation

$$v = \sqrt{\frac{2ma}{\rho C_d A}}$$

In case you are struggling with the plugging the numbers in, this is an example using the values for the golf ball.

First write out each letter with its corresponding value – these can be found on the previous slide

m = 0.046, a = 10, ϱ = 0.82, C_d = 0.4, A = 0.0014

Now replace each letter in the equation with its value (Yes - you will need a calculator)

$$v = \sqrt{\frac{2 \times 0.046 \times 10}{0.82 \times 0.4 \times 0.0014}}$$

$$v = 44.8\text{m/s}$$

Note: All your answers will be in meters per second

Correct order

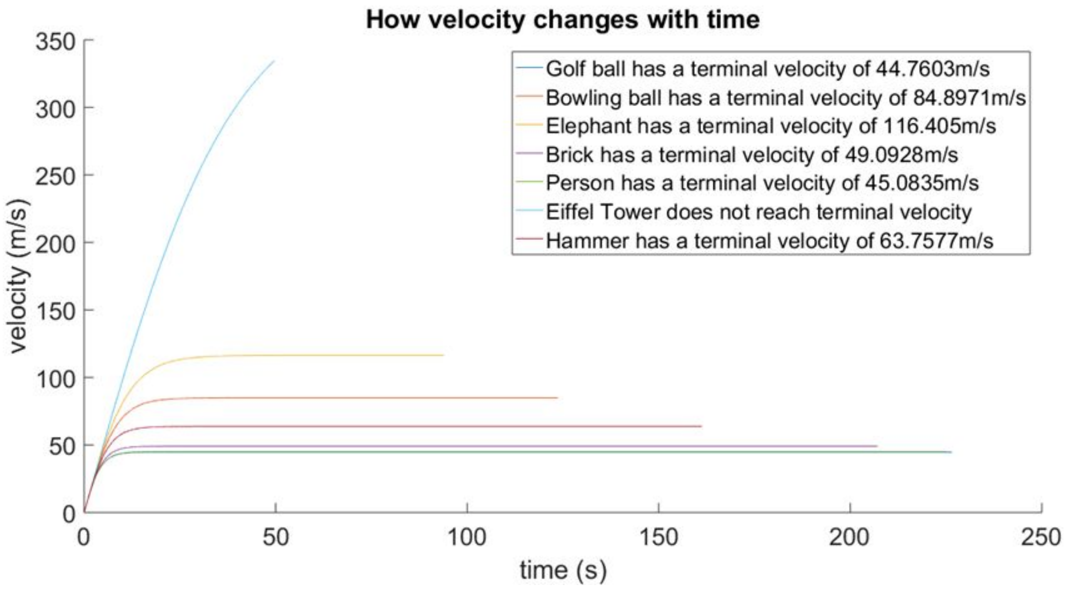
You can now hopefully compare your prediction with the correct answers below

Plots of how their velocity and height above the ground change are shown on the next slides

Try using the excel spreadsheet included to see what happens when you change the object properties.

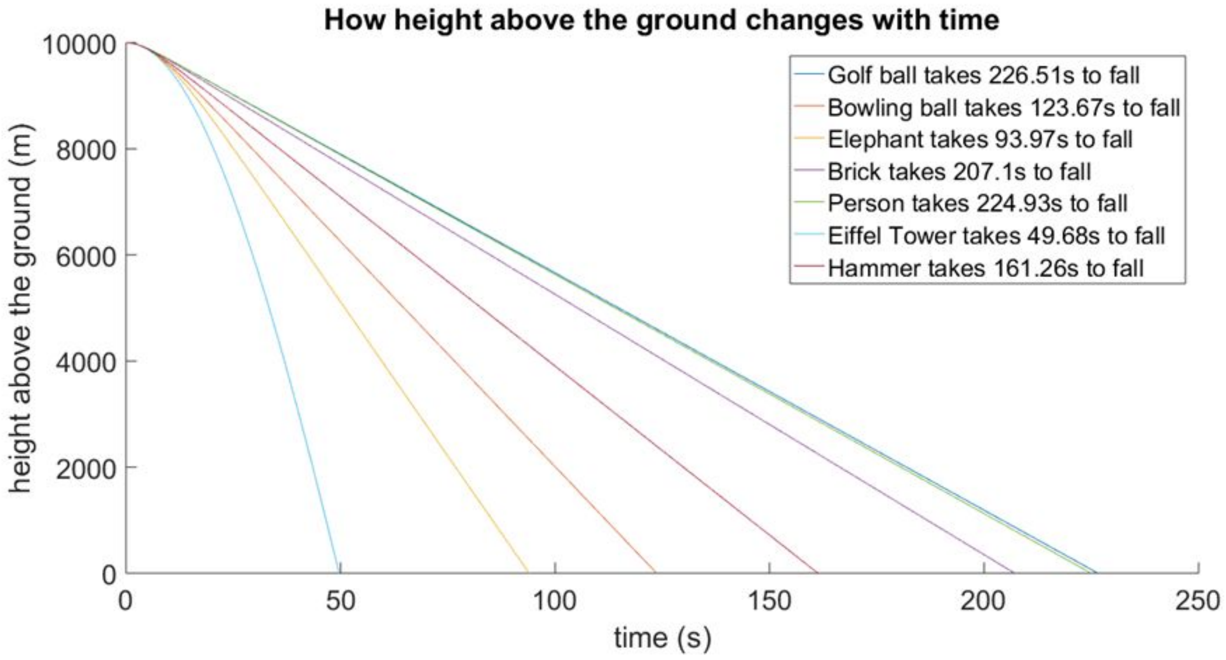
Object	Terminal velocity m/s
Eiffel Tower	392.5
Elephant	116.4
Bowling ball	84.9
Hammer	63.8
Brick	49.1
Person	45.1
Golf ball	44.8
Feather	0.31

How velocity changes with time

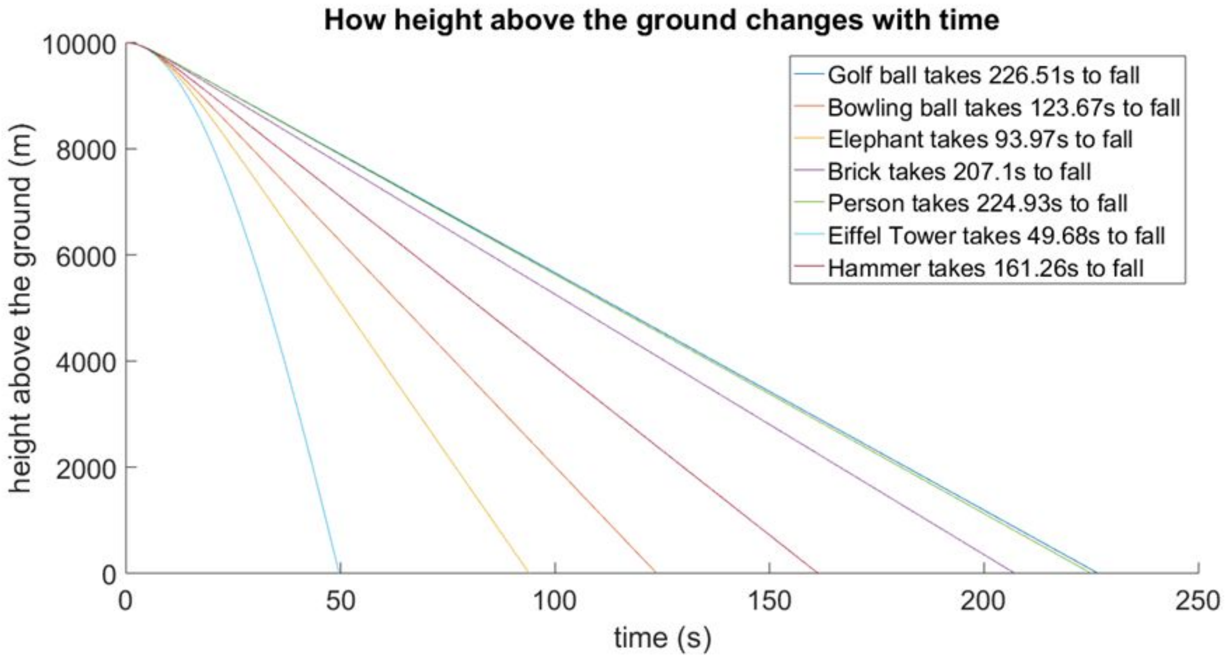


How can you tell the Eiffel Tower does not reach terminal velocity

How height above the ground changes



How height above the ground changes



Further thinking

Now that we've seen how objects fall in air, we can think about how the same objects would fall in different condition.

Use what you have learnt about forces on a falling body and drag to explain what would happen if a feather and hammer were dropped from the same height at the same time on the moon.

The video below is from Apollo 15 and shows what happens.

https://moon.nasa.gov/resources/331/the-apollo-15-hammer-feather-drop/

To help you answer the question think about:

- The forces on a falling body
- What the air is like on the moon
- How the air impacts drag

Task to win Prizes

Task:

- Design and build a parachute for an egg using only the set of materials listed
- The parachute should be designed so that when the egg does not crack when it is dropped from a certain height
- By changing the properties of the parachute, including the amount and shape of the parachute material, the number of strings and the method of attachment, the parachute will be less/more effective at increasing the time to fall
- The time of fall should be measured (using a stopwatch) for a range of different drop heights
- Graphs of Fall Time vs Drop Height should then be plotted to study how these variables are related.

Parachute Project – Material Required

- Plastic bag
- String
- Eggs
- Tape measure / ruler
- Paper
- Sellotape
- Stopwatch

Parachute Project – Process

Steps:

1. Cut out a section of material, in any shape you think would be suitable for a parachute
2. Attach the outer edges of the parachute material to the egg
3. Gradually increase the height of your drop until the egg cracks. Once this happens, rethink the design of the parachute to see if you can stop the egg cracking
4. Change the properties of your parachute to maximise the drop height – eg: size of parachute, length of string, parachute shape etc, then make some conclusions about which properties increase/decrease the effectiveness of the parachute.

Keep track of your changes and why you choose the design you pick, points will be awarded for this. Back up your changes with reasons as to why the changes were made.

Parachute Project – Final Challenge

- This is the time in which you must perfect your parachute design, using everything you have learned so far
- Having investigated the impact of the following parachute properties:
- Parachute size
- Parachute shape
- Amount of material
- Attachment method
- Length of string
- Perfect your parachute design, and then drop your parachute and egg at the maximum height
- Make sure you take a video or a photo of your hi drop to send to your teacher as evidence of your drop time
- The best parachute is not necessarily the winner. The marking criteria is on the next slide
- Good luck!

Parachute Project – Marking Criteria

How points will be awarded to win prizes:

- The maximum drop height of the egg
- The creativity of the design
- The graphs you plot of fall time vs drop height
- The conclusions you draw on the relationship between mass and drop time
- How well the information is presented – the format is up to you

Summary

From today's session you should:

- Be aware of Newton's First and Third Law, and see how these are applied to all moving objects.
- Know what factors change the amount of drag and why
- A well-engineered and awesome looking parachute.
- Be confident in setting up and running an experiment independently.
- Have had fun!! (Most Importantly)

There are some questions on the following slides to test your understanding of what you have learnt. You're not being marked on these answers so don't worry if you struggle with anything. Your teacher will have the solutions if you need them.

Questions

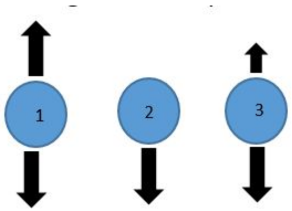
1. If the Space Shuttle is travelling at its touchdown velocity of 220 mph (≈100 m/s), how long would it take to cover the 5 mile (≈8000 m) length of the runway if it didn't slow down?

2. The Space Shuttle deploys its parachute at the start of the runway but it doesn't come to a stop in time.
   a. How could the designers decrease the stopping distance of the Shuttle?
   b. At touchdown, with the parachute deployed, what forces are exerted upon the Shuttle? (Hint: draw a force diagram like the ball in the lesson pack)
   c. What could have potentially happened if the designers make the parachute too big? (Think a little outside the box on this one)

3. Assuming a parachute is at a height of 15 m off the ground, and is falling at its terminal velocity of 2.5 m/s. How long will the can take to hit the ground?

Questions

4. A ball was dropped from rest and the forces acting on the ball at different stages of its fall are shown below. Which image shows the ball travelling with the highest velocity



5. Once the ball reaches terminal velocity, it opens a parachute. Draw force diagrams to show the forces acting on the ball when:
   a. The parachute it first deployed
   b. A couple of seconds after the parachute has been deployed
   c. A long time after the parachute has been opened

6. It is commonly said that there is no gravity is space. Is this true?