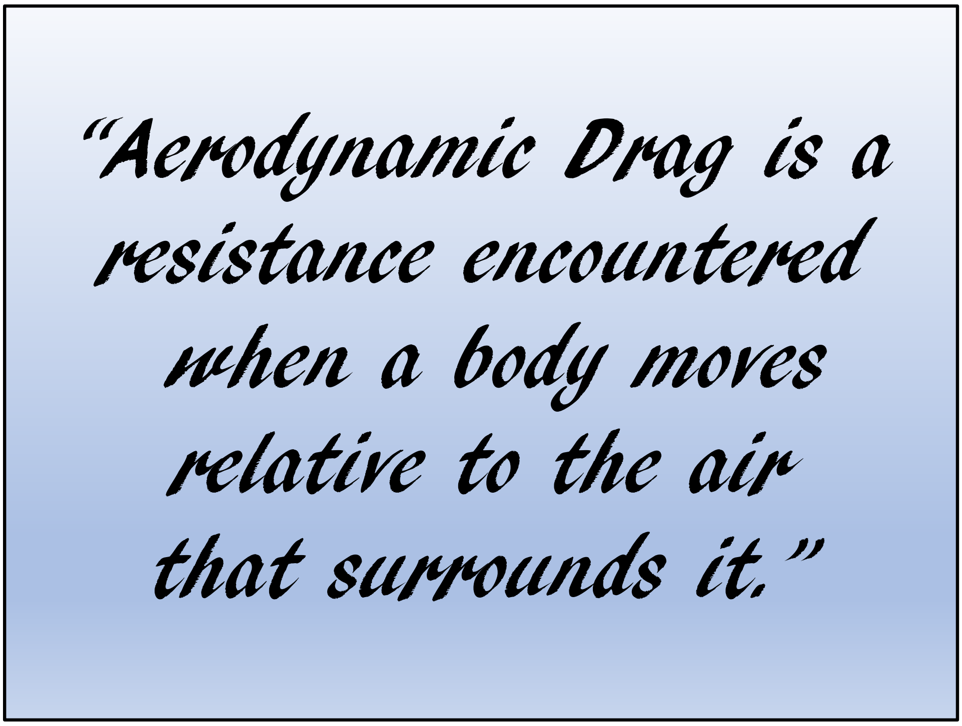
Second Level Technologies
Benchmark SCN 2-20a

Physics of Flight Pt 4

Exploring the science of the force of aerodynamic drag.

The trouble
with
Aerodynamic Drag.

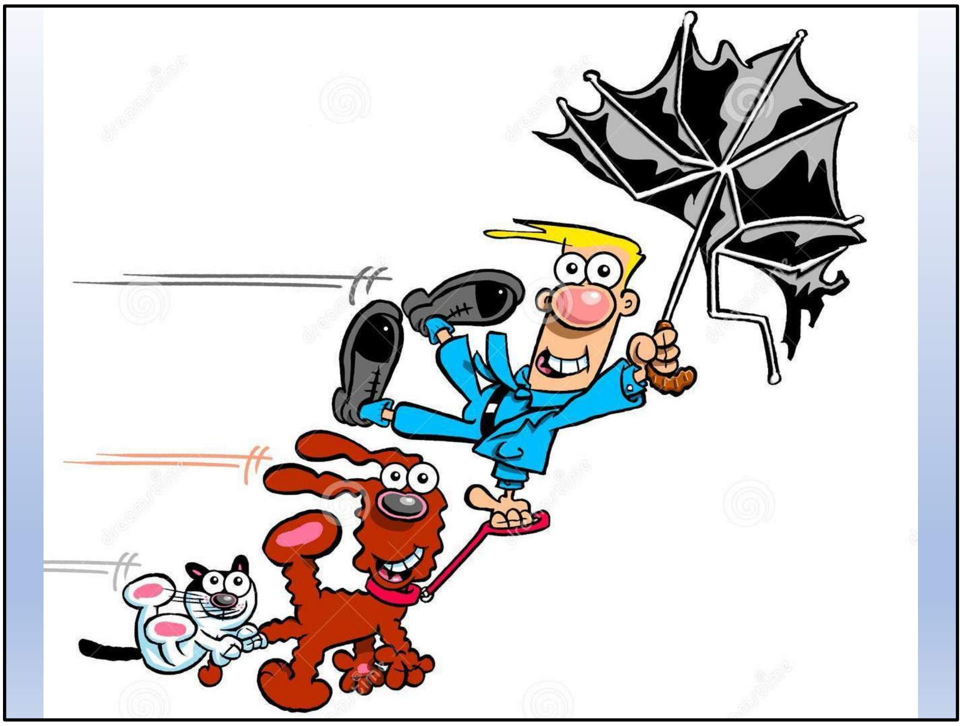


“Aerodynamic Drag is a resistance encountered when a body moves relative to the air that surrounds it.”

When we try to move quickly through the atmosphere that surrounds our planet, we will discover that there is a force holding us back.

Similarly, if the atmosphere travels quickly past us, we will notice the same force trying to move us. When the atmosphere moves we call it wind.

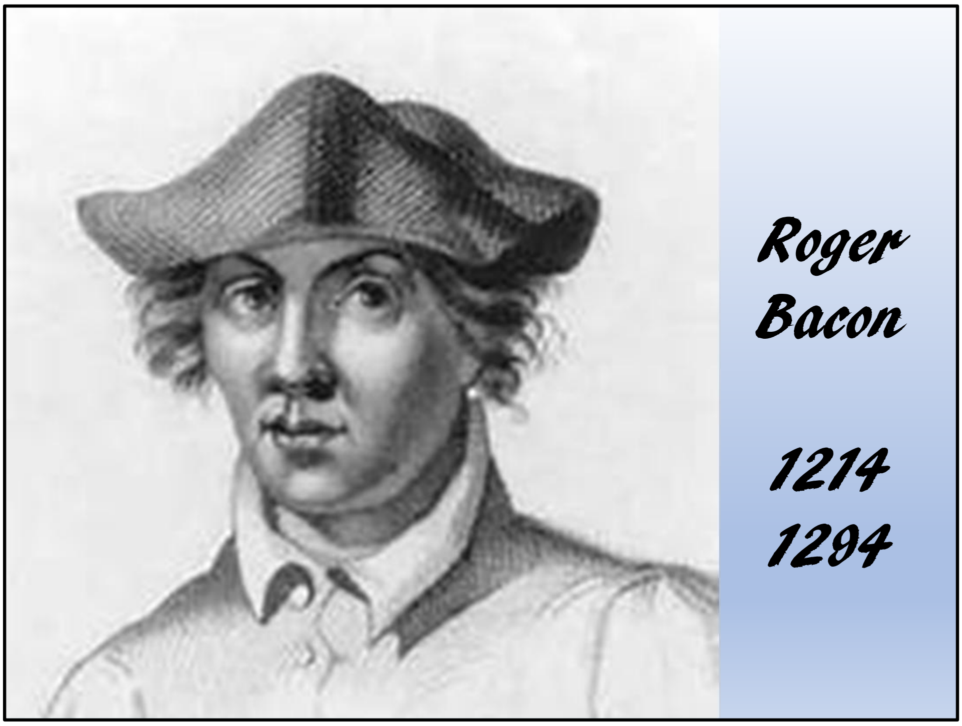
Early humans did not know what caused this but they knew that when the wind blew strongly, the force got a lot worse. [click]



The first life on our Earth started in the oceans and there are still more species of animals in the sea than on land. However, some life broke free of the sea and started the long process of evolution that eventually produced mankind who evolved a questioning brain that needed answers to everything. It was very difficult to explain many of the things that happened around us.

Early man did not know that he was completely surrounded by our atmosphere, it could not be seen, so why would he know it was there. It seemed that the only explanation for natural events would be to claim that they were the work of the Gods. For instance, wind could be explained by having wind gods.
The Ancient Greeks gave the wind gods names and they also assumed that the Sun and Moon must be gods driving their chariots across the sky.

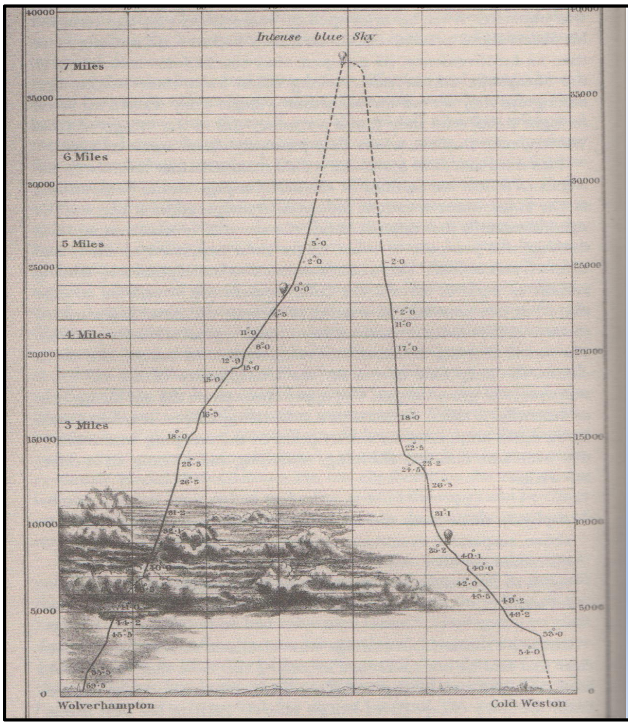
The concept that we were living at the bottom of a shallow pool of a mixture of gases, that we call air, did not occur to them.

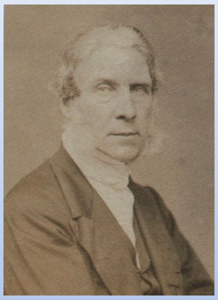


Roger
Bacon

1214
1294

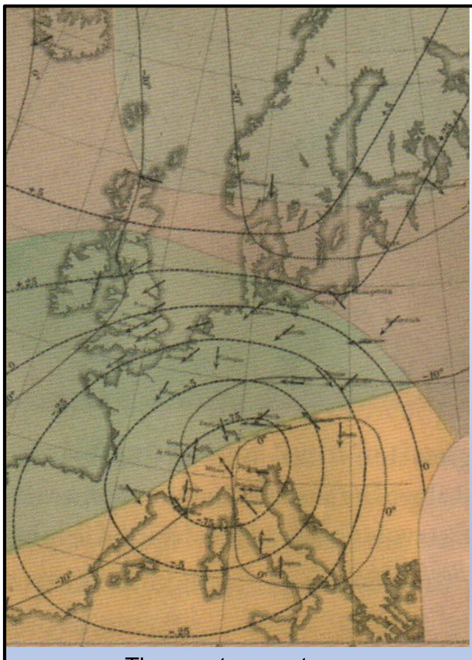
People were quite happy with these explanations of natural phenomena until this man came along. Roger Bacon was a philosopher, the old name for a scientist, and he thought a lot about many things that puzzled him. He lived in a monastery and every so often he had to take his turn at collecting water from the river. He noticed that when he dipped a bucket into the fast flowing river that he had to hold on tightly to stop the bucket from being dragged out of his hand. He knew why that happened. He had to carry two full pails of water back to the monastery so he was well aware that water was heavy. However, he also noticed that on windy days the wind tried to knock him off-balance when carrying the pails. He suddenly realised that the wind, just like water, must be heavy also and, when it moved, it had enough weight to knock him about. This was a revelation but Roger at that stage did not know what the atmosphere was and it was much later that scientists discovered that our atmosphere was a mixture of gases, that we call air, and also they discovered just how heavy it really was.



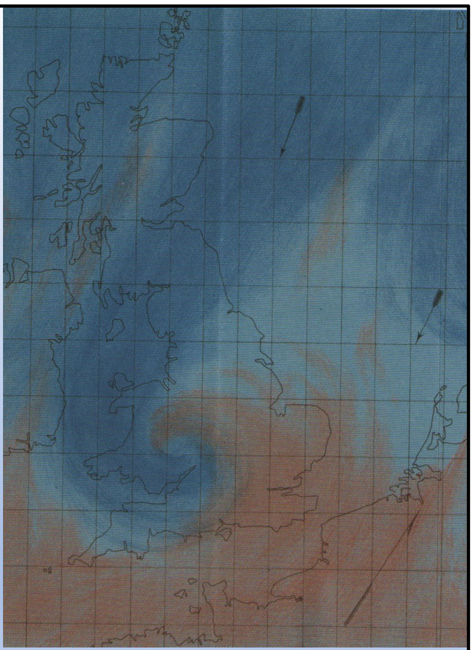

James Glaisher

In1862 two very brave British weathermen, James Glaisher and Henry Coxwell, decided that they should see how high they could get in a gas balloon and take readings of temperature, barometric pressure and humidity during the trip. The balloon was called “Mammoth” and was filled with coal gas. This chart shows the ascent and descent of the balloon. The flight lasted about 2 hours and travelled about 40 miles.

This trip very nearly killed them. Glaisher started to succumb to lack of oxygen at about 25,000 feet and was vaguely aware of Coxwell climbing up into the rigging of the balloon to free the rope that he had to pull to open the gas vent at the top of the balloon. Coxwell then fell down into the basket on top of Glaisher who he thought was dead. The balloon got to its highest altitude of about 35,000 feet before it started to descend. When the balloon descended back down through about 20,000 feet both men slowly recovered and continued to record data during the descent. They were not put off by this frightening experience and continued to carry out many other high altitude flights and discovered many peculiar facts about the upper atmosphere such as varying air temperatures and conflicting wind directions.

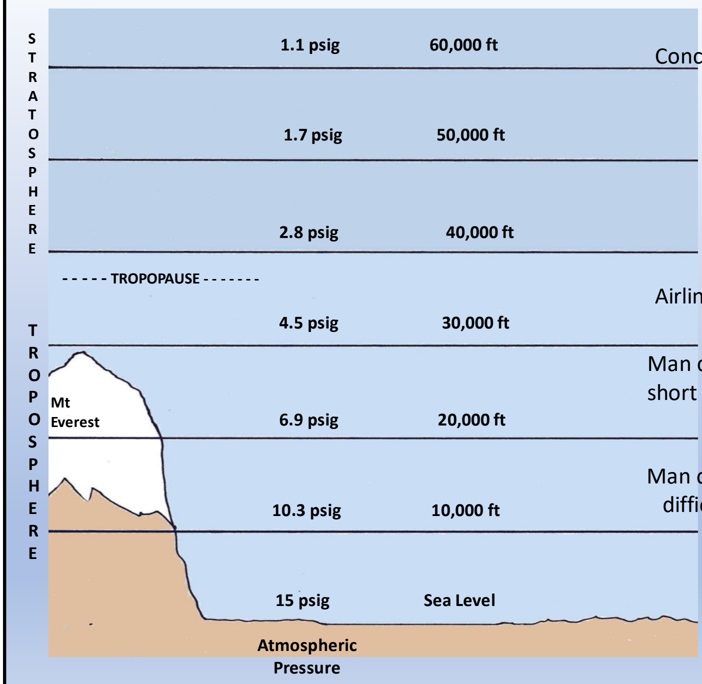


The great snowstorm of Christmas 1836



The storm that sunk the ship, the Royal Charter, with great loss of life.

It was not until the 19th century that scientists made a serious attempt to discover how weather works. They tried to find out what caused the storms which were very damaging and were responsible for driving hundreds of ships onto rocks and drowning thousands of sailors and passengers. Oddly enough it was the development of railway systems in America, and their use of the telegraph to control the trains, that made it possible to find out what the weather was doing at the same time all over the country. The American scientists discovered that when the weather reports were plotted on a map it could be seen that winds had a circulatory motion. They discovered that cyclones, which were the damaging strong winds, rotated in an anticlockwise direction but the larger areas of less strong winds rotated in a clockwise direction. We now know that the circulation of the winds is caused by the heating effect of the sun and the rotation of the earth. The two charts shown above, drawn in the middle of the 19th century, look very similar to the weather charts that we see on television today. By putting together all the information from many weather stations the weather men were able to see what had caused severe weather events. But it was to be many years before there was enough information to be able to forecast what the weather might do in the future.



Concorde flew up here.

Airliners fly up here.

Man can only survive for very short periods at this height.

Man can only survive with difficulty at this height.

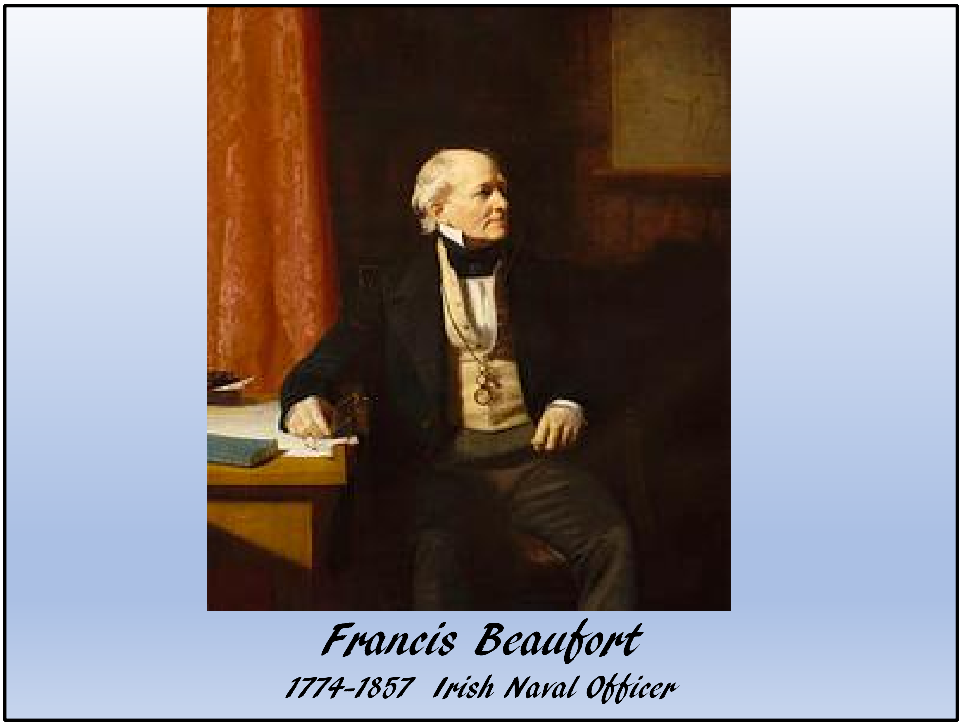
This diagram shows how the atmosphere changes with altitude. Note how the capability of humans is limited by increasing altitude.
Relative to the total population of the world, only very few people live above the 10,000 ft altitude. Almost all of the worlds population live near to, or at, sea level and mankind has adapted very well to living at this height, in fact it is so normal that we do not think about the pressure that the atmosphere is subjecting us to.
Passengers flying on airliners at about 35,000 ft have to be artificially protected from the effects of altitude by pressurising the cabin to achieve an altitude of usually less than 8,000 ft inside the cabin.

Exploring Wind Force and Aerodynamic Drag

Even before early mankind understood what wind was, it was discovered that it could be used to good effect. When men started to use small boats to travel along the coastline they discovered that if the wind was going in the same direction they could hold up a small square of matting and the wind would provide a force to help move the boat. When men discovered how to weave fabrics and how to make bigger and stronger sails it was found that boats could be made bigger and moved with less effort.

Early Greeks and Romans expanded their travels and empires using boats and, over the centuries, the development of sailing ships reached a high standard. ***This photo shows a replica of the Argo, the ship that Jason and the Argonauts used in about 300 BC, to sail across the Aegean Sea into the Black Sea in search of the Golden Fleece.*** However these sailing ships still were useless if the wind was blowing in the wrong direction. New trade routes were eventually developed where it was known that the prevailing winds blew constantly in the same direction. We now call these kind of sailing ships “square rigged” ships and they work best when the wind was blowing in the direction of travel.

Later, in the 8th and 9th centuries the Vikings developed very light but very seaworthy ships that they used to explore, raid and settle all over Europe and across the Atlantic via Iceland and Greenland to North America. Note how these ships were provided with oars so that they could still make progress when the wind blew in the wrong direction.

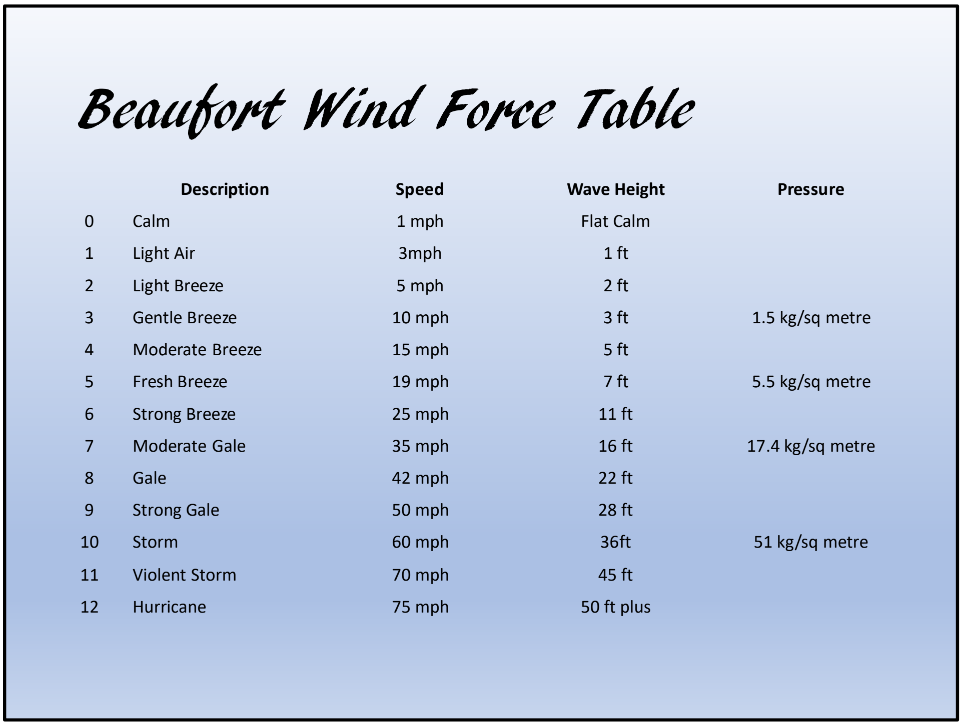


Francis Beaufort

1774-1857 Irish Naval Officer

In Britain, during the16th century, the great variety of fighting ships operating under the direction of the various monarchs for the last 1,000 years, were drawn together into the official British Navy. The development of the square rigged battle and support ships accelerated so that the British eventually had the largest navy in the world.

In 1805 an Irish Sea Captain, Francis Beaufort, decided that the strength of wind had to be described much more accurately. This was in the days of sailing ships so he was mainly concerned with the effect of wind on the sails of ships.



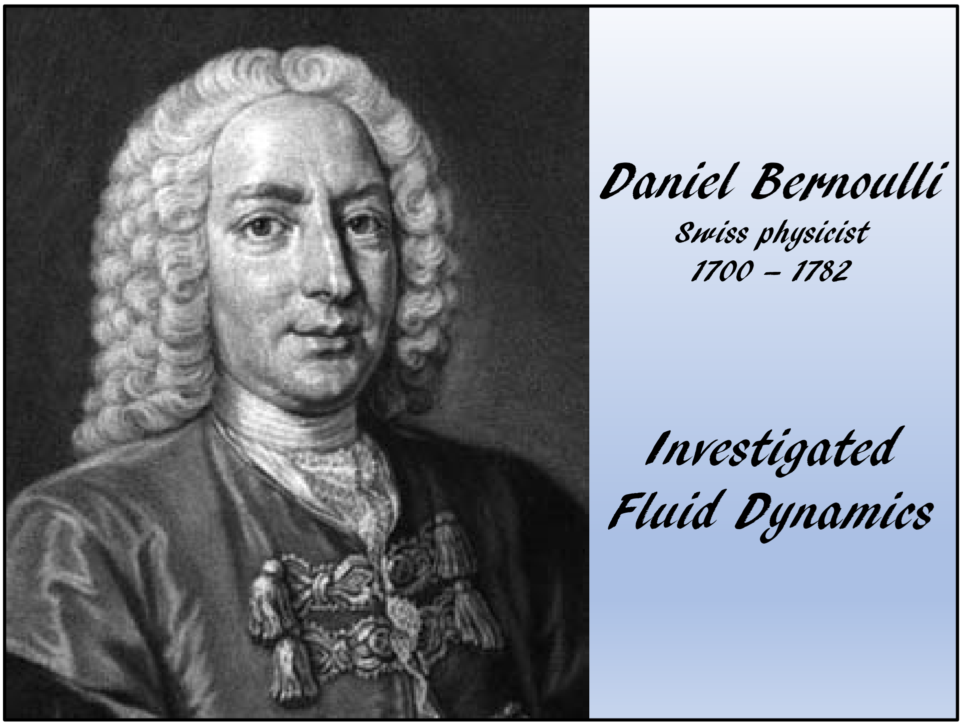
Beaufort Wind Force Table

	Description	Speed	Wave Height	Pressure
0	Calm	1 mph	Flat Calm	
1	Light Air	3mph	1 ft	
2	Light Breeze	5 mph	2 ft	
3	Gentle Breeze	10 mph	3 ft	1.5 kg/sq metre
4	Moderate Breeze	15 mph	5 ft	
5	Fresh Breeze	19 mph	7 ft	5.5 kg/sq metre
6	Strong Breeze	25 mph	11 ft	
7	Moderate Gale	35 mph	16 ft	17.4 kg/sq metre
8	Gale	42 mph	22 ft	
9	Strong Gale	50 mph	28 ft	
10	Storm	60 mph	36ft	51 kg/sq metre
11	Violent Storm	70 mph	45 ft	
12	Hurricane	75 mph	50 ft plus	

He divided the wind strength up into twelve levels of severity. For instance, wind force 1 was just enough to move the ship and it could only be steered with difficulty, at wind force 6 the ship could just carry full sail but wind force 11 was strong enough to rip sails to shreds and blow them off the spars. Later on when steam ships were introduced it was more important to know what the sea state would be like with the various wind strengths. So the Beaufort wind force table was modified to the one that is used in modern weather forecasts.

The important thing to notice about the wind force shown in Captain Beaufort’s wind tables is that as the wind speed increases the wind pressure increases but at much greater rate. If the wind speed increases from 10 to 20 mph the wind speed doubles but the wind pressure increases by 4 times. If the wind speed increases from 10 to 30mph the speed goes up 3 times but the pressure goes up 9 times. Also if the wind speed increases from 10 to 60 mph the speed goes up 6 times but the pressure goes up 36 times. This is called the square law, more about this later.

The ultimate design in square rigged ships was probably achieved in the trading ships known as “Clippers”. Probably the most famous of these was the Cutty Sark built on the Clyde in 1869. The long narrow hull of wooden planking on iron frames could carry over 1,000 tons of freight. The Cutty Sark had *32 sails of total area 3,000 square metres*
Top speed in this ship was 17.5 knots [20mph] and, on a good day, could travel nearly 400 miles. The Cutty Sark set a sailing ship record by carrying wool from Australia to Britain in 73 days. However, sail was soon to be replaced by steam.



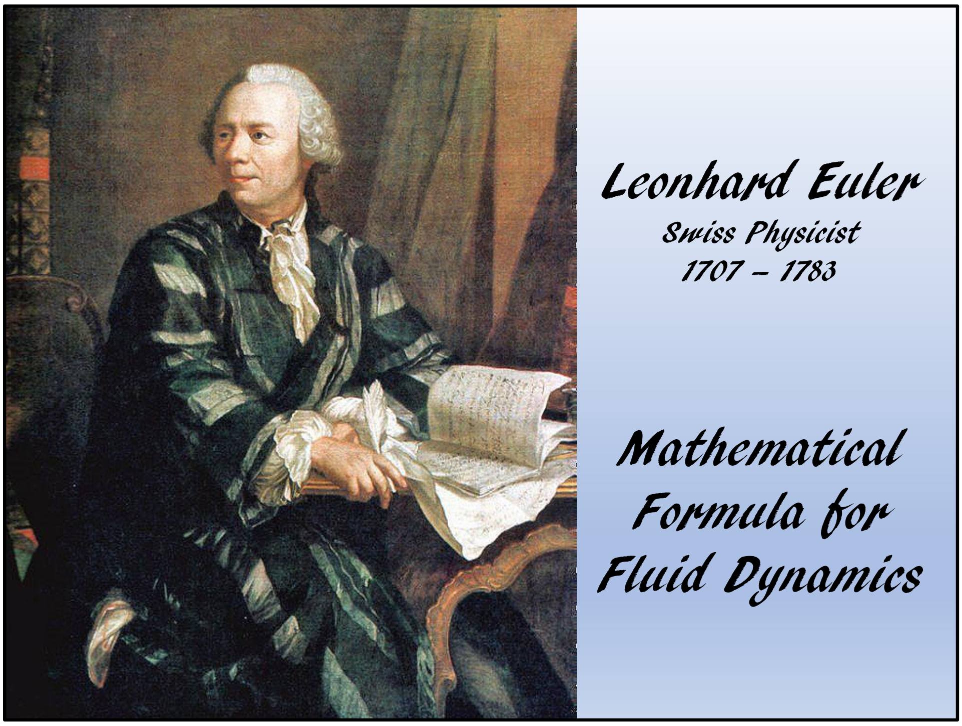
Daniel Bernoulli

Swiss physicist

1700 – 1782

Investigated Fluid Dynamics

However we now need to go back a century to find out where the “square law” came from. Daniel Bernoulli, a Swiss physicist, was carrying out some experiments with water flowing in pipes and through holes. He discovered various interesting things and one of them was that when the water flowed its pressure dropped.



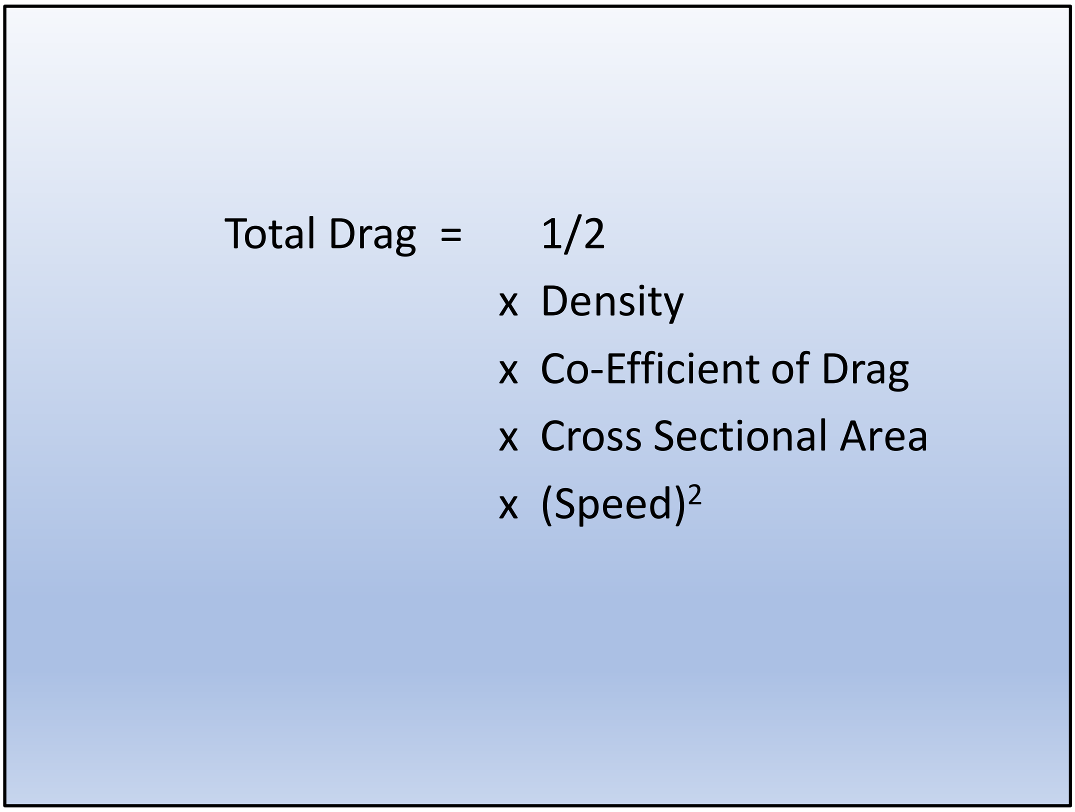
Leonhard Euler

Swiss Physicist

1707 – 1783

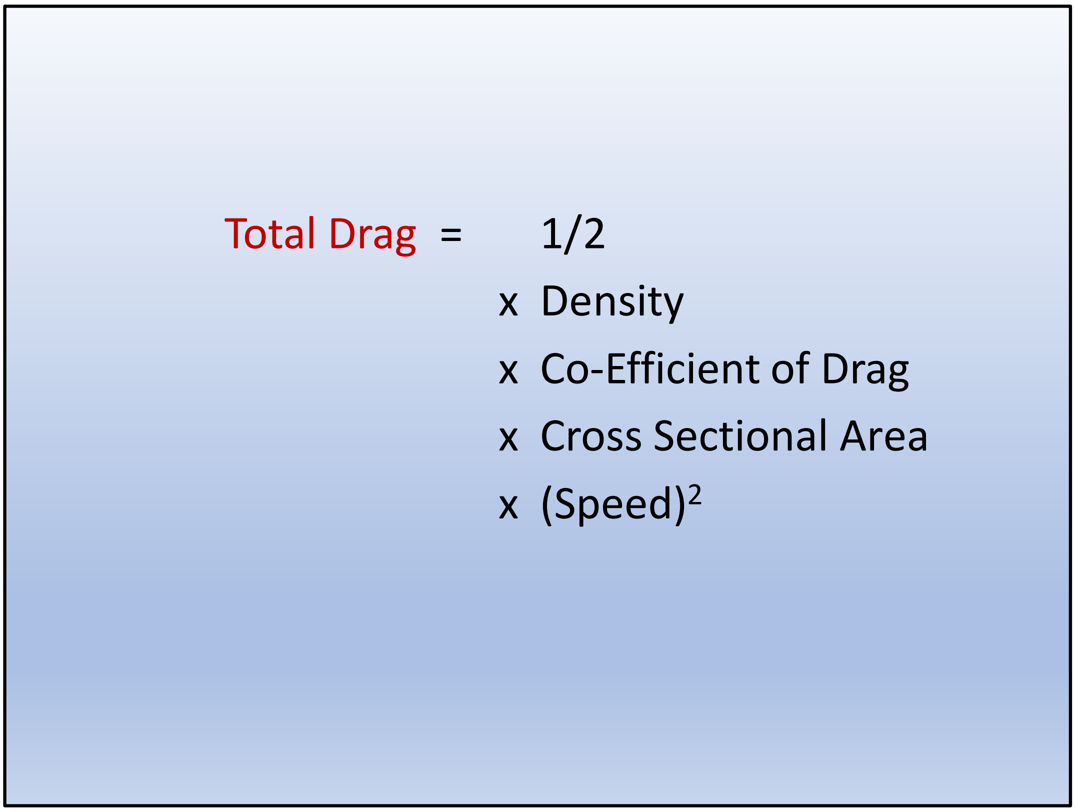
Mathematical Formula for Fluid Dynamics

Leonhard Euler was a mathematician and he was also interested in Bernoulli's experiments and was able to quantify the results in a mathematical formula which allows us to calculate the drag of an object moving through a fluid.



Total Drag = 1/2
x Density
x Co-Efficient of Drag
x Cross Sectional Area
x (Speed)^2

This is the formula that Euler devised and it looks very complicated, but it is not as bad as it looks.
Let’s look at each of these items in turn *(Click)*



Total Drag = 1/2
x Density
x Co-Efficient of Drag
x Cross Sectional Area
x $(\text{Speed})^2$

The Total Drag is how much the medium through which you are travelling is slowing you down. It is a quantity that describes the difference you feel between walking along normally and walking in a swimming pool. It is a much more difficult in the swimming pool, and the Total Drag will be higher.
The other terms are what determines how hard this is. Let's consider them.
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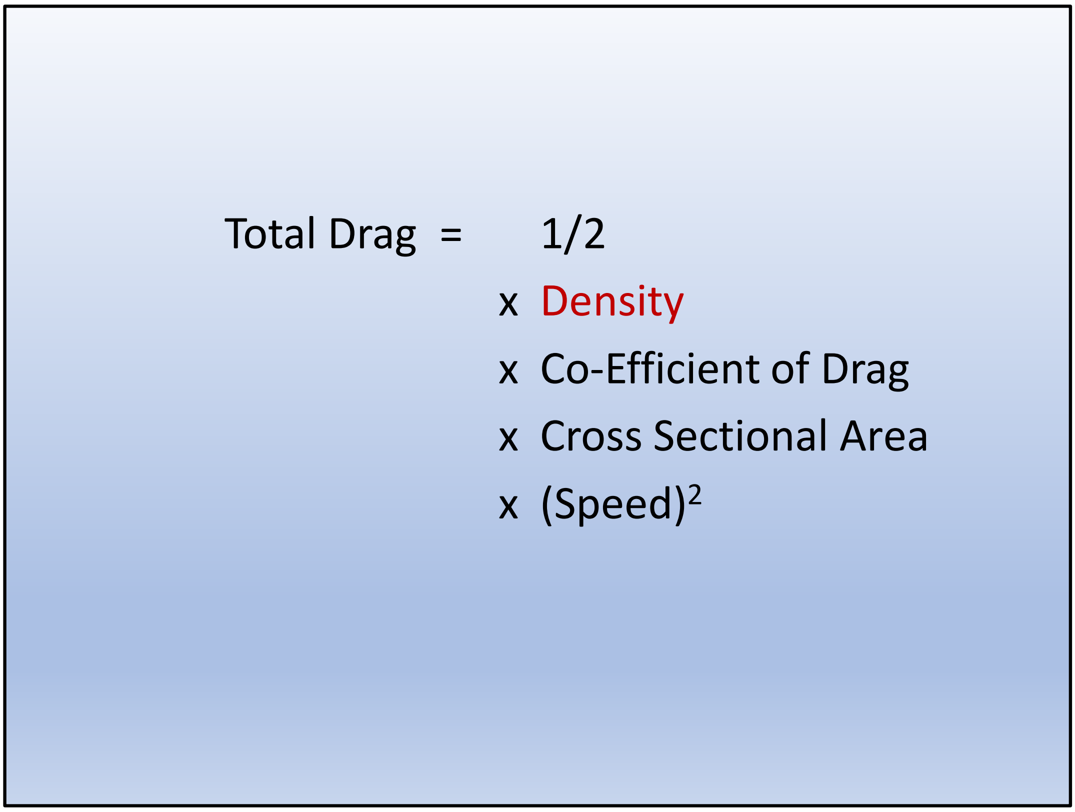

Total Drag = 1/2
x Density
x Co-Efficient of Drag
x Cross Sectional Area
x (Speed)^2

The density is simply how ‘thick’ the medium is. Staying with the swimming pool example, walking in the swimming pool is much harder because water is much ‘thicker’ (or more dense) than air. How hard would it be walking in treacle? Or walking in a vacuum?
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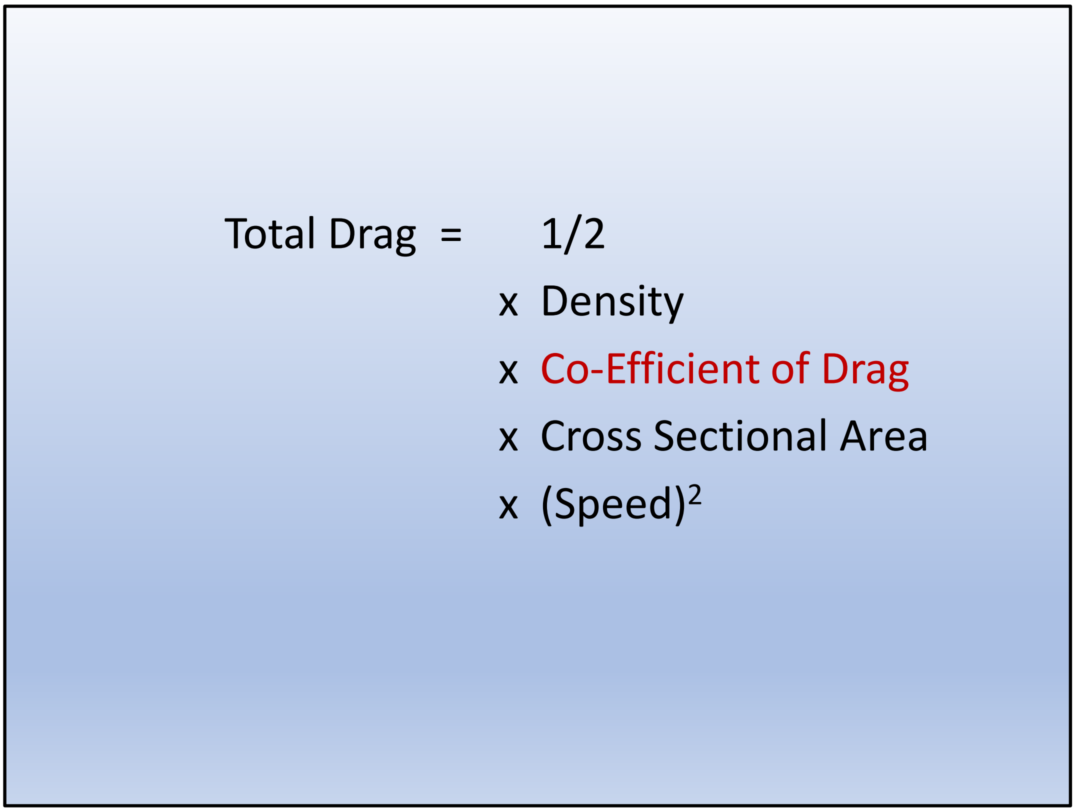

Total Drag = 1/2

x Density

x Co-Efficient of Drag

x Cross Sectional Area

x $(\text{Speed})^2$

What else might impact on the Total Drag? If you think about aeroplanes or racing cars or anything that is designed to go fast, it looks like it will go fast. In fact they have been designed to go fast. If you chopped the pointy end off an aeroplane and replaced it with a flat plate, would it go as fast? Intuitively you expect that it wouldn't. We'll find out why in a minute, but the Co-Efficient of Drag is a quantity which describes the shape of an object. It is small for sleek, pointy shapes and large for flat awkward ones.

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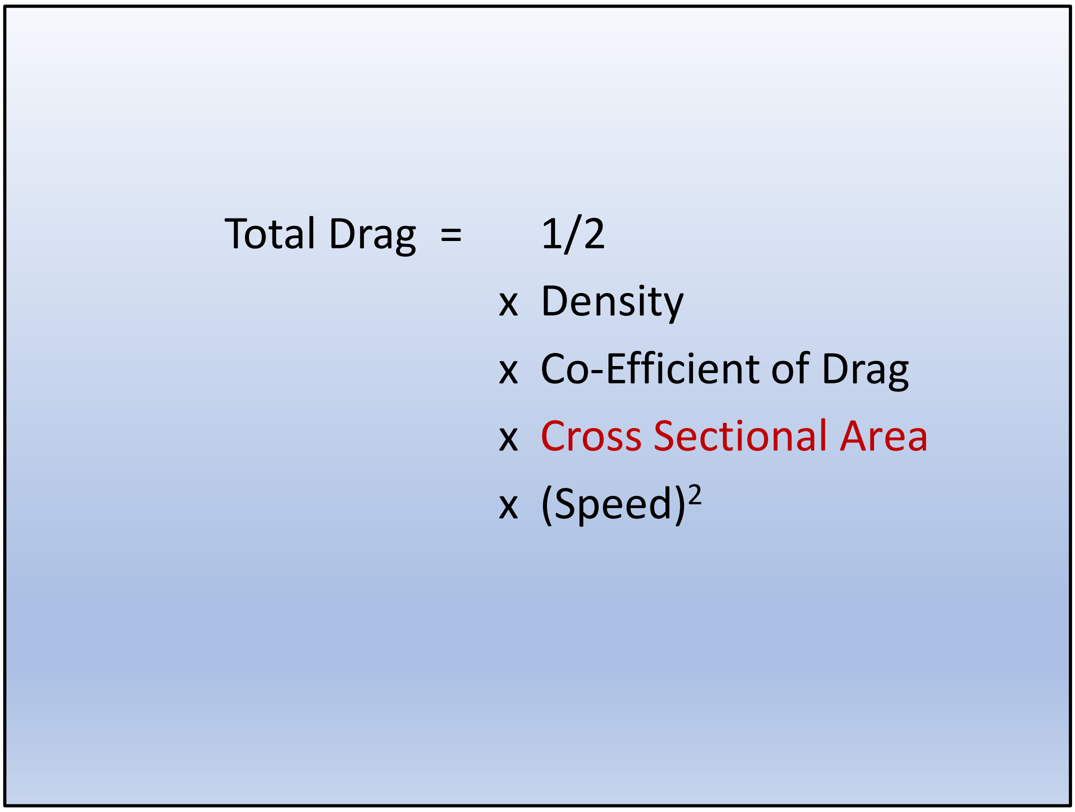

Total Drag = 1/2

x Density

x Co-Efficient of Drag

x Cross Sectional Area

x $(\text{Speed})^2$

The cross sectional area of an object has an impact on the amount of drag – try holding on to a large flat sheet of plywood or sheet metal on a windy day.
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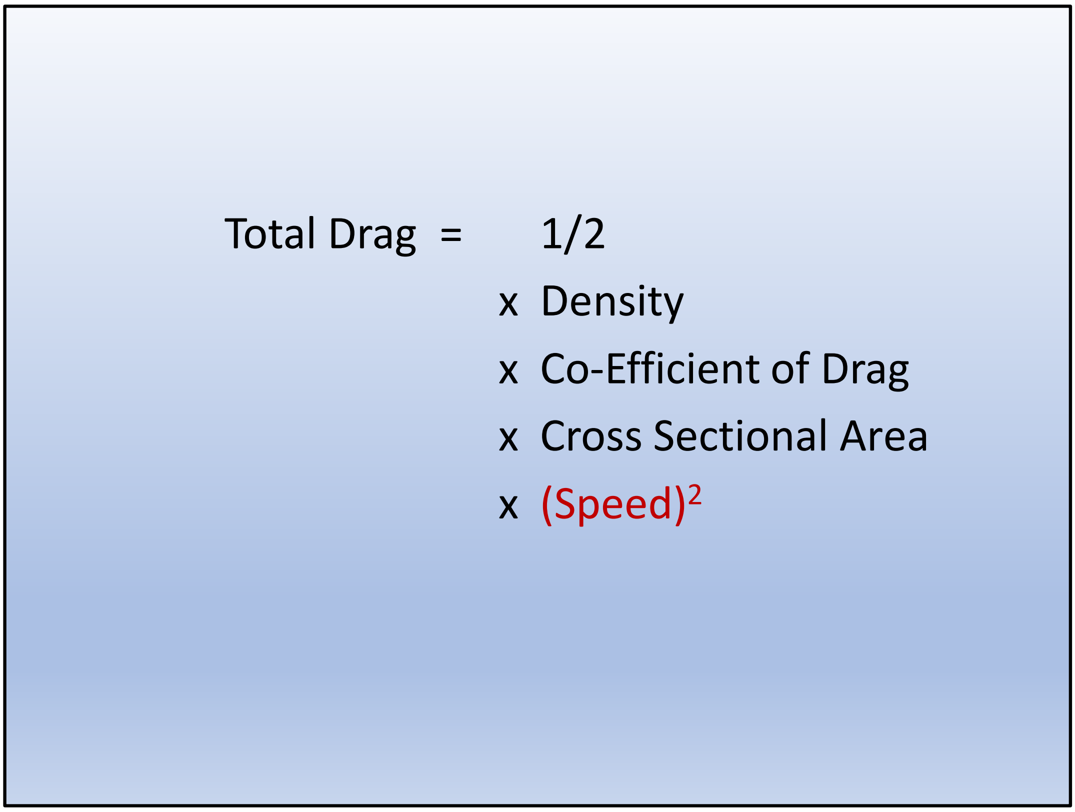

Total Drag = 1/2
x Density
x Co-Efficient of Drag
x Cross Sectional Area
x (Speed)^2

Going back to the swimming pool example again, if it hard to walk in a swimming pool, try running! It is even harder.
This term is different to the others though, because it is squared – that’s what the little ‘2’ indicates – and that means
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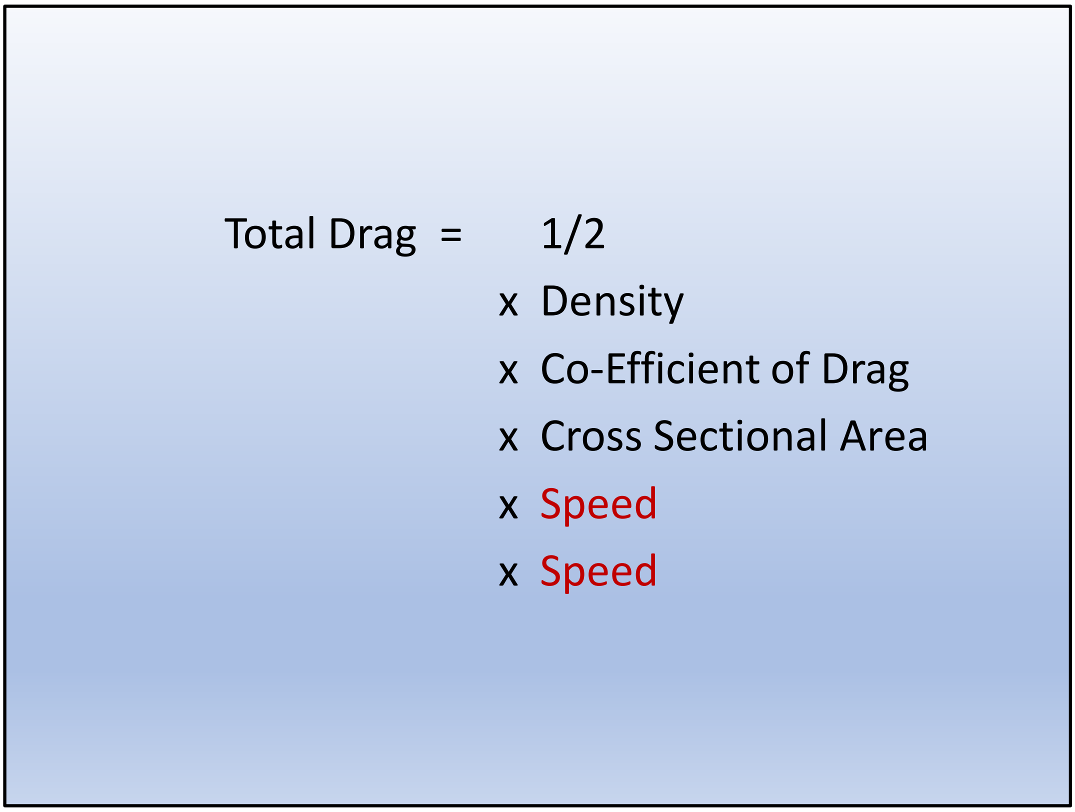
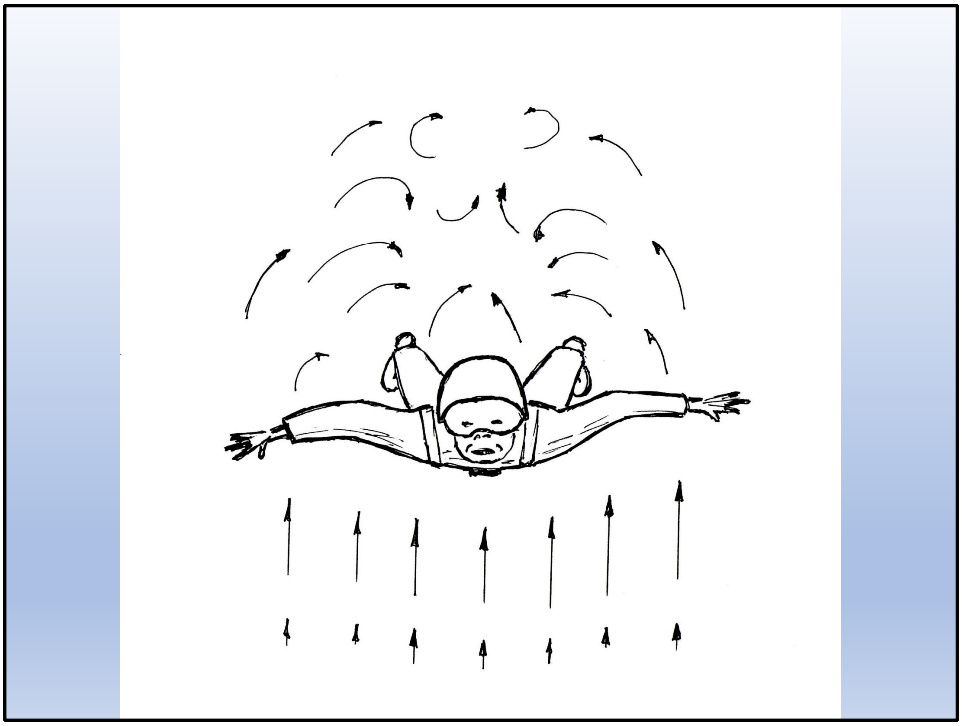


Total Drag = 1/2
x Density
x Co-Efficient of Drag
x Cross Sectional Area
x Speed
x Speed

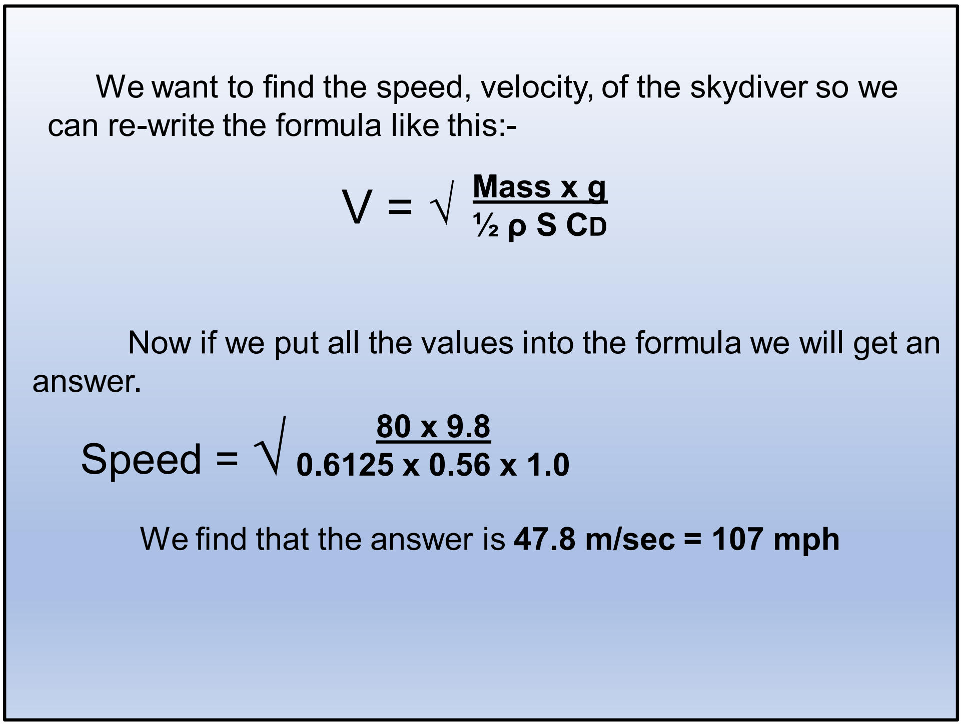
speed x speed. Put another way, as we saw earlier, if we double the speed we quadruple the drag. If we triple the speed we multiple the drag by nine. How much will the drag increase by if we multiply the speed by 4? And by 5?

So Total Drag = ½ times density times co-efficient of drag times cross sectional area times speed times speed.

We can use this formula to look at some practical examples and see the impact of changing some of these quantities



Now that we have a formula that would allow us to calculate drag, let's see if we can use it to find out some things. **Lets go skydiving.** Before we jump out of the door of the aircraft we need to know something about the skydiver. What is their weight? We could assume that dressed in full kit they would have a mass of 80 kg. Now we need to know the diver's cross-sectional area with arms and legs spread out. This is a bit more difficult but we could estimate an area of 0.56 square meters. So now we can calculate how fast we can fall during the skydive.



We want to find the speed, velocity, of the skydiver so we can re-write the formula like this:-

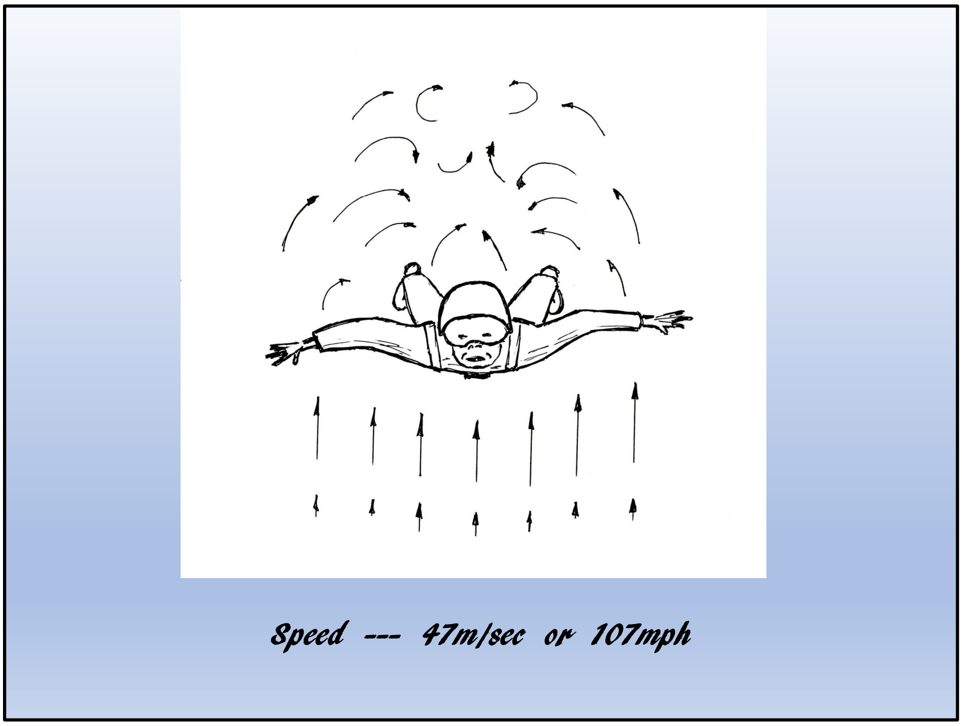
$$V = \sqrt{\frac{\text{Mass x g}}{\tfrac{1}{2}\rho\, S\, C_D}}$$

Now if we put all the values into the formula we will get an answer.

$$\text{Speed} = \sqrt{\frac{80 \times 9.8}{0.6125 \times 0.56 \times 1.0}}$$

We find that the answer is **47.8 m/sec = 107 mph**

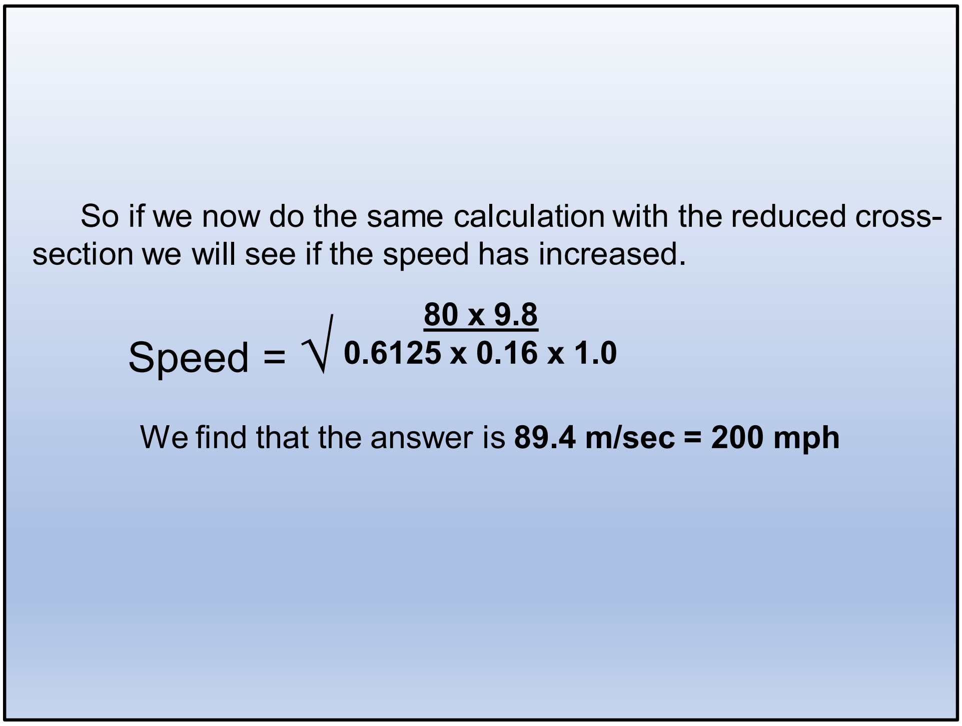
So now we have almost all the information we need to calculate the speed of the skydiver but we need to move the units of the formula around to give the answer that we want. The last bit of information that we need is the density of the air and in this case we can assume that the value will be 1.225 kg/m^3 at an altitude of 1,000 feet where our skydiver will open his parachute.



Speed --- 47m/sec or 107mph

Here is a skydiver in a standard free-fall position with arms and legs stretched out to increase the cross sectional area and wearing loose clothing which increases the co-efficient of drag.

Assuming that the diver is quite close to the ground (but hopefully not too close) and using the formula we can calculated that the diver will be falling at 47 metres per second or 107 miles per hour when the parachute is opened.



So if we now do the same calculation with the reduced cross-section we will see if the speed has increased.

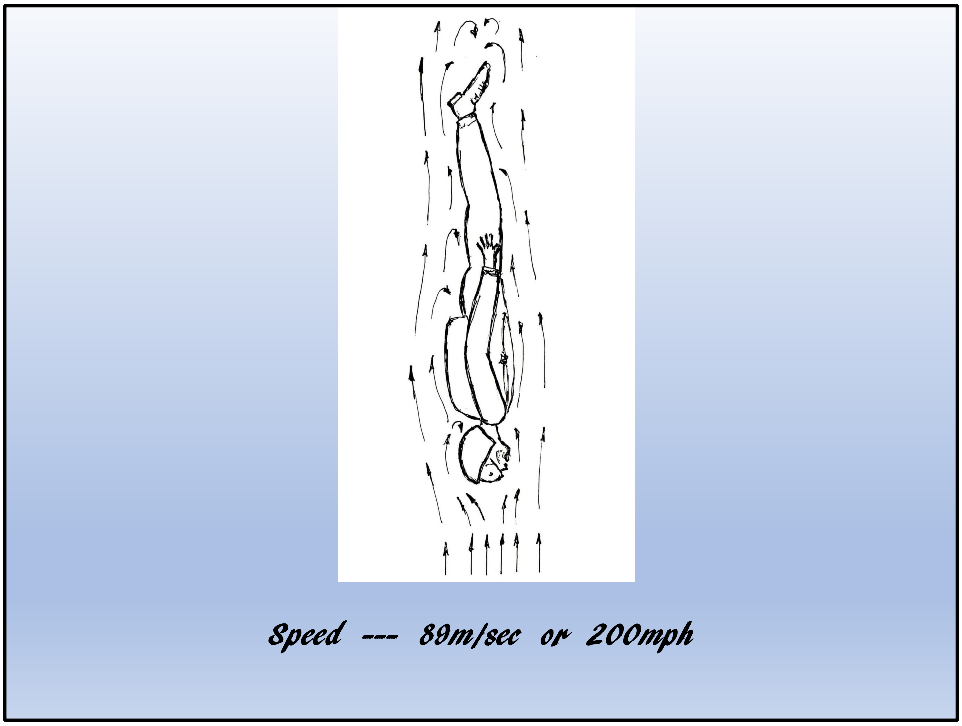
$$\text{Speed} = \sqrt{\frac{\mathbf{80 \times 9.8}}{\mathbf{0.6125 \times 0.16 \times 1.0}}}$$

We find that the answer is **89.4 m/sec = 200 mph**

So now we know that our sky diver would be travelling at 107 mph when the parachute opens.

If we wanted to see how fast the diver could go we could try something else. We cannot change the force of gravity, the mass or the density of the air but we could change the cross sectional area.

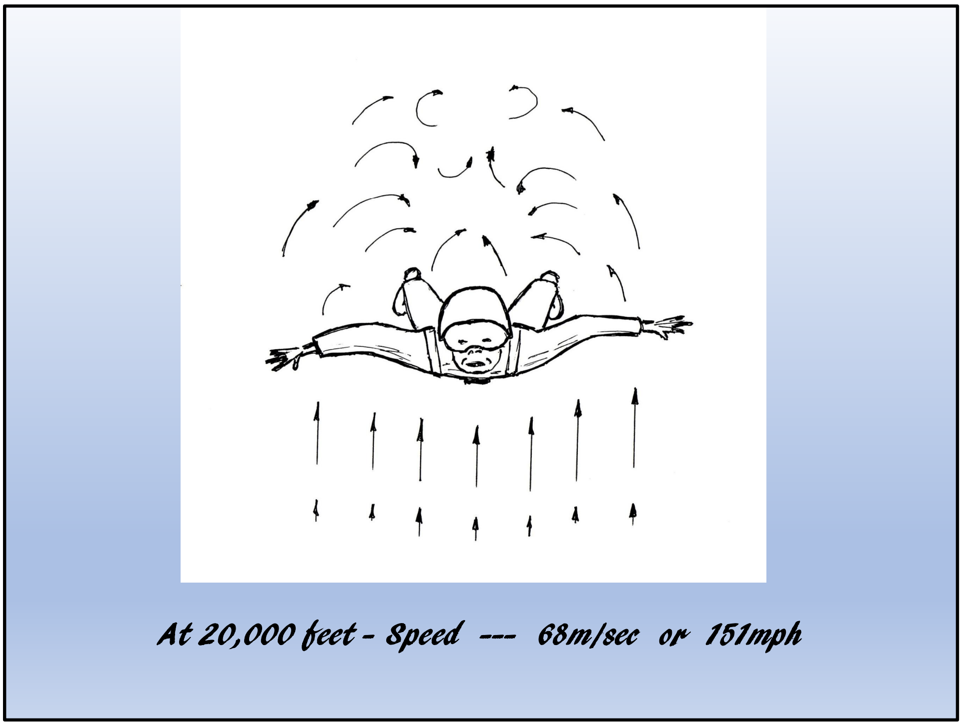
If we rotate to fall head-first we could reduce our cross-sectional area from 0.56 m² to about 0.16m².



Speed --- 89m/sec or 200mph

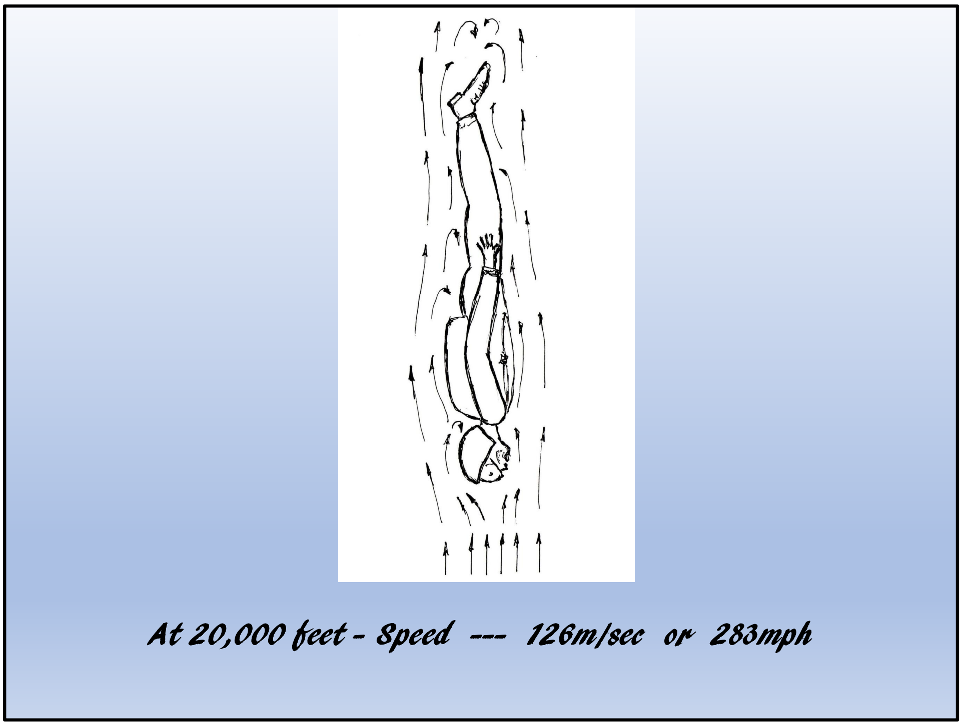
Now the skydiver has reduced the cross sectional area by pointing straight at the ground and is holding both arms back so that the loose clothing cannot fill with air and so reducing the coefficient of drag.

The calculation now shows that by reducing the cross-section the speed has increased to 89 metres per second or 200 miles per hour.



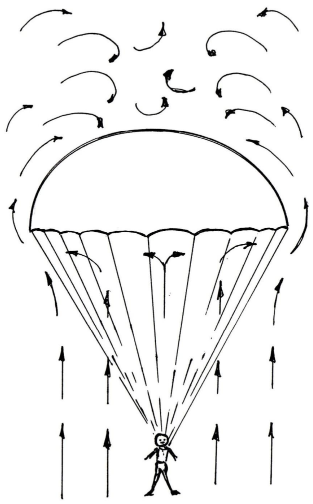
At 20,000 feet - Speed --- 68m/sec or 151mph

So far in our calculations we have assumed that the density of the air is constant and that the sky diver is quite near the ground. But air gets thinner as you go higher or, put another way, the density of the air reduces with increasing altitude.
So now if we were to jump out of an aircraft at 20,000 feet the air density is only half of that at sea level.
The first problem is that we will have to take some oxygen with us to make sure that we do not pass out since that would make it difficult for us to keep track of our height which is quite important when you are sky diving.
Because the air at this altitude is quite thin, that is less dense, we can move through the air with less resistance and can therefore go much faster.
So we can use the same formula again to find our speed at this altitude is 68m/sec or 151mph.



At 20,000 feet - Speed --- 126m/sec or 283mph

Repeating the same calculation for the ‘headlong’ dive, but this time at 20,000 feet shows that the sky diver is now travelling at 126 metres per second or 283 miles per hour.



Speed --- 5m/sec or 12mph

We can quite easily make ourselves bigger by spreading a large sheet of cloth above our heads. This is what we call a parachute. Also we can change the co-efficient of drag by making the parachute a particular shape which will make it more difficult to pull through the air. In fact a parachute is about the worst possible shape to pull through the air, which is good if you want to slow down, but useless if you want to travel through the air at speed. Note how the parachute leaves a very confused wake as the air struggles to flow round its shape.

Now if we do the same calculation using the area of the parachute and the increased co-efficient of drag we can now calculate the new speed of descent – 5 metres per second or 12 miles per hour.

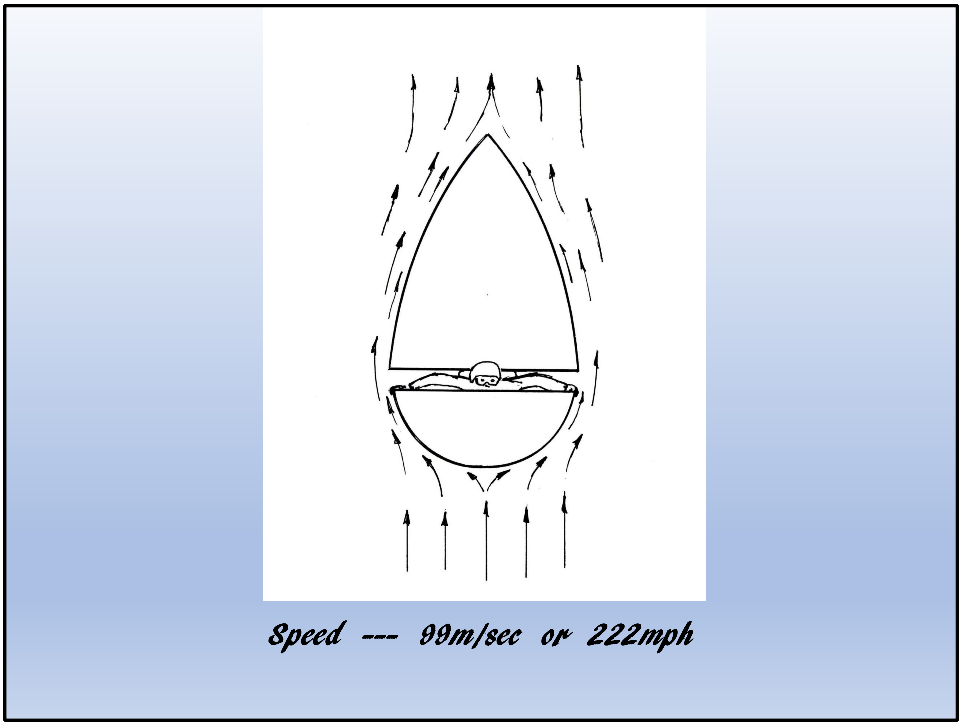
So, by using the formula defined by Euler all those years ago we have been able to find out quite a lot about our speed when we go skydiving.

Now we know that if we jump out of an aircraft at 20,000 feet and dive head-first we will accelerate quickly to about 280 mph. Then if we turn over onto our face with arms and legs spread out we will quickly slow down to about 150mph. If we now rotate back into the head-first position we will again accelerate to about 200 mph. But now as we descend the air becomes more dense and we will gradually slow down. Now, to be able to safely open our parachute, we will have to again rotate onto our face with arms and legs spread out. We will now quickly slow down to about 107 mph.

You may think that it is curious that the skydiver will slow down the nearer he gets to the ground, but that is the case.

When we open our parachute we will be slowed very quickly to 12 mph and we will hit the ground at that speed.

So now we have learned something about “drag” and how it can limit the speed at which we can travel through the air.



Speed --- 99m/sec or 222mph

Our skydiving shape turns out to be poor for travelling at speed. In fact skydivers wear loose fitting jumpsuits so that they flap about at speed and create quite a lot of drag. Skydivers normally want to spend as long as possible in free-fall, so that they can practice manoeuvring around before they have to open their parachutes. So as we have found out, a skydiver will reach a “terminal velocity” where the air drag will exactly equal the weight of the skydiver.

(Click)

If we want to move through air quickly we need to change our shape to something that the air can flow round easily. We call this “streamlining”.

A streamlined shape has a rounded nose and a long smooth tapered tail. You may have noticed that racing cyclists wear strange shaped hats with long tails to reduce the drag of the shape of their heads. Aircraft usually are shaped in a similar way to reduce drag. If the shape of the nose and tail are designed correctly the drag of the object can be reduced significantly.

So now let us see what happens if we “streamline” our shape when we are skydiving. We could wear a special suit that has a rounded nose on our chest and a long tail on our back.

We have not changed our position, we still have arms and legs spread out. Our weight has not changed much and the force of gravity remains the same however the streamlining will reduce the co-efficient of drag quite considerably. So now if we do the same calculation we will see that the speed has increased to 99 metres per second or 222 miles per hour (near the ground). We have doubled the skydiver’s speed by adding the streamlined fairing.

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So now we can see why aircraft have rounded noses and tapering rear fuselages. Modern aircraft like this Airbus A350 are very efficient because the drag has been reduced to the minimum.