VISUAL PHYSICS
School of Physics
University of Sydney *Australia*

FLUID FLOW
MOTION OF OBJECTS IN FLUIDS

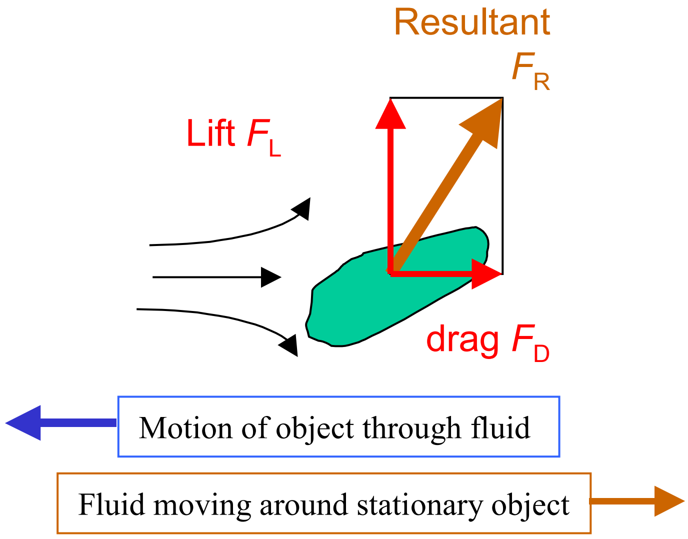
? How can a plane fly?
Why does a cricket ball swing or a baseball curve?

In the real world all objects move through fluids so we must include the forces exerted by the extremely large number of fluid molecules. In some situations the effect of these forces can be ignored (eg motion of tractors and farm machinery), in others they play a crucial role in determining the motion

- racing cars
- sports - swimming, running, cycling, flight of cricket balls.
- dispersal of plant seeds
- aerosols
- motion of molecules in the circulatory system
- sedimentation of soil particles
- exchange/transfer of molecules.....oxygen gas is denser than nitrogen gas. Why doesn't the atmosphere stratify into a layer of oxygen near the earth's surface and a layer of nitrogen above it?

FORCES ACTING ON OBJECT MOVING THROUGH FLUID

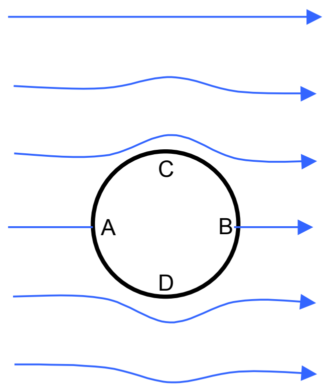
!



Consider an object moving through a fluid. F_R represents the resultant force acting upon the object. This result force F_R can be resolved into two components

- Drag force F_D - directed opposite to the motion of the object or in the direction of the flow advancing into the object.
- Lift force F_L - at right angles to this direction.
  Only a drag force can act on a symmetrical object (F_L = 0).

Uniform motion of an object through an ideal fluid ($\eta = 0$)



Identical to when the fluid is moving with the same velocity relative to a the stationary object (Galileo's principle of relativity).

Since an ideal fluid has zero viscosity, it should slide freely over the object's surface and completely around it. Consider the flow of a fluid around a very long (infinite) cylinder. The pattern must be completely symmetrical around the cylinder because the fluid flows completely around it. The pressure near point A and B will be the same (and greater than in the undisturbed flow because the velocity near these points is lower – streamlines further apart). The pressure near points C and D will also be the same (lower than in the undisturbed flow because the velocity near these points is higher – streamlines closer together). Consequently, the result force on the object to the pressure acting on the surface is zero, therefore no drag or lift.

The pattern is symmetrical $\Rightarrow F_R = 0$

? What about the motion through a viscous fluid?

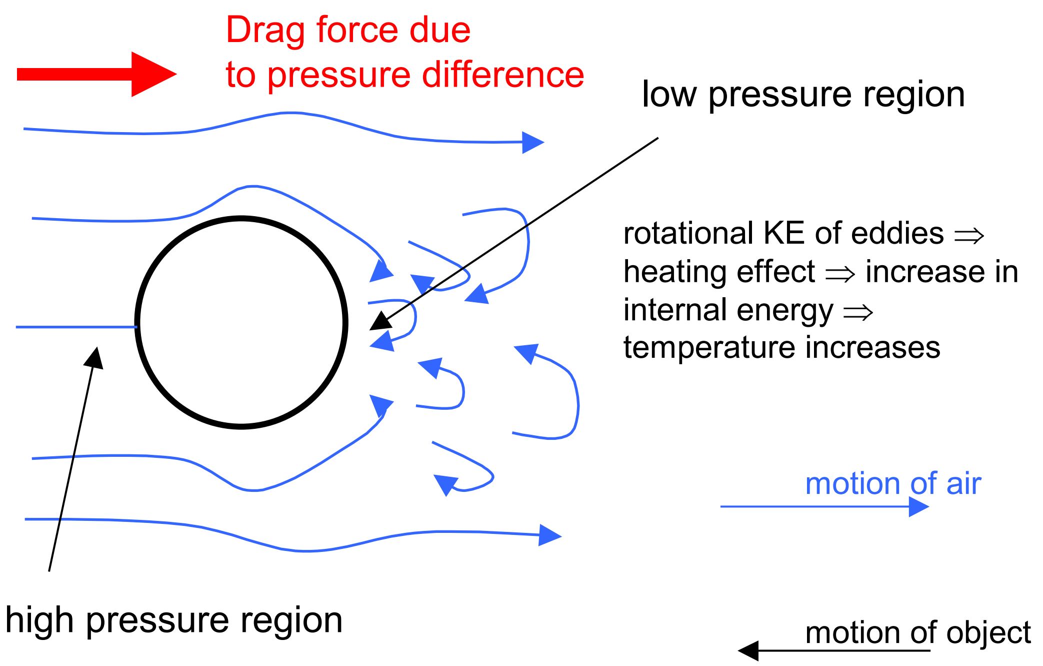
! A very thin layer of the fluid adheres to the object's surface and moves together with it as a single whole carrying along adjacent layers of the fluid due to friction (viscosity). The velocity of these layers decreases with distance from the object's surface and at a certain distance the fluid is virtually undisturbed by the motion of the object. The object is surrounded by a layer of the fluid in which there is a velocity gradient. This layer is called the **boundary layer**. Therefore the frictional forces between the layers and hence surface of the object create the drag force acting on the object.

The presence of a boundary layer radically changes the nature of the flow around the object. Complete flowing around the object becomes impossible and the flow breaks away fro the object's surface resulting in eddies behind the object. The eddies gradually attenuate and their energy is dissipated by heating the fluid. The pressure in the eddy region is lowed and a pressure difference now exists across the object giving rise to the **drag force**.

! Thus drag consists of

- frictional drag (viscosity)
- pressure drag (eddies – lower pressure)

The magnitude of the pressure drag force is very dependent upon the size of the cross sectional area and shape of the object. Objects with a well streamline tear-drop shape have the smallest pressure drag. The shape of a plane's body and wings are of extreme important in determine the amount of drag.



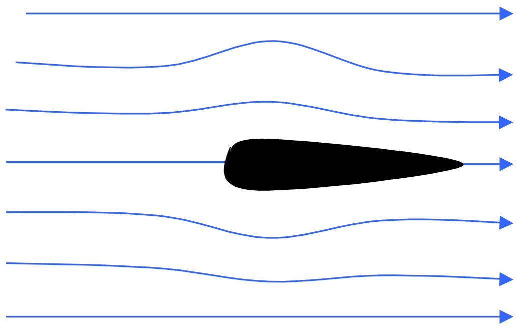
The ratio between the friction drag and the pressure drag is determined by the value of Reynolds number ($R_e = \rho\, v\, L / \eta$)

R_e small (viscosity) $\Rightarrow$ friction drag > pressure drag
R_e very large (speed of fluid) $\Rightarrow$ pressure drag > friction drag

A model of an aeroplane will behave in a gas flow the same as the full scale counterpart if in addition to geometrical similarity of the model and the aeroplane, the Reynolds number is the same for both.

Reynolds number is an important parameter in describing the motion

$$R_e = \rho\, v\, L / \eta$$



Tear drop shape for streamlining

Simple models for the motion of an object through a fluid

A simple model to describe the drag force (very complex) is

$$F_D = b\, v + c\, v^2$$

Where b and c are constants that depend upon the properties of the fluid and shape of the object.

$b\, v$ dominates at low speeds (small Reynolds numbers)

$c\, v^2$ dominates at high speeds (large Reynolds number)

$F_D = b\, v$

R_e small $\Rightarrow$ $v\, L$ small $\Rightarrow$ drag depends also solely on friction and the pressure force can be ignored. Applies to objects of diameter less than about a millimetre moving in water or air, or larger objects moving in more viscous (sticky) fluids.

When radius of the object << dimensions of the fluid

$$F_D = 6\,\pi\,\eta\,R\,v$$

Stokes' Law (George Stokes 1919 – 1903)

$F_D = c\,v^2$

- Cars and planes.
- Birds of prey, initially traveling faster than their terminal velocity are slowed down to terminal velocity by the drag force.

$$F_D = \tfrac{1}{2}\,\rho\,A\,C_D\,v^2$$

ρ density of fluid

A maximum cross sectional area presented by moving object

C_D drag coefficient – dimensionless number, depends on shape of object Streamline object $C_D \sim 0.1$ Awkward shape $C_D > 1$ Streamline cars $C_D \sim 0.3$

Terminal speed v_T

Parachutist reaches terminal speed ($a = 0$) $\Rightarrow$ weight = drag force

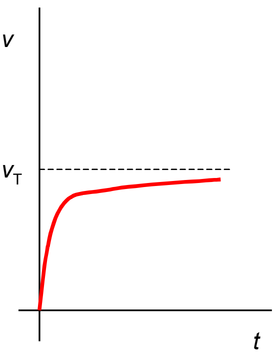
$F_D = \tfrac{1}{2}\,\rho\,A\,C_D\,v^2$

$F_G = m\,g$

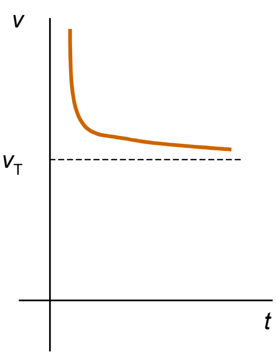
$F_D = F_G$

$v_T = \sqrt{(2\,m\,g / \rho\,A\,C_D)}$

parachutist $v_T \sim 10$ km.h^{-1}



Object falling from rest



Object thrown down with initial speed $v_0 > v_T$

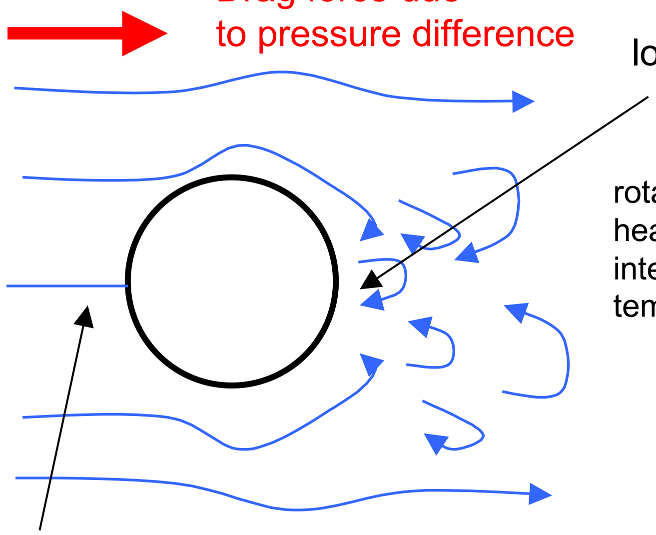
? Why does a ball curve in flight? – golf, cricket, table tennis balls

From simple projectile motion theory Tiger Woods should only be able to hit the ball 100 m. Why can he hit the ball > 300 m?

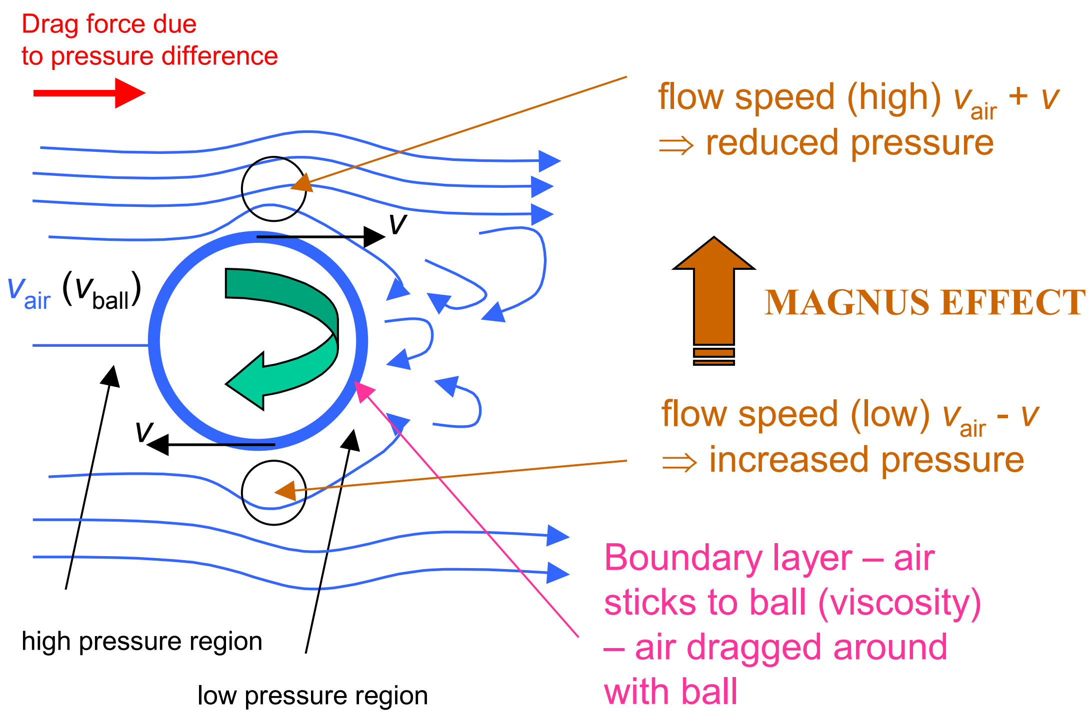
Magnus Effect

A ball needs to be spinning to curve. Air “sticks” to the ball due to viscosity (internal friction) and so a layer of air is dragged around with the rotating ball. So on one side of the ball the air will be moving faster than on the other side ⇒ turbulence is asymmetrical ⇒ when the air is moving more quickly the pressure will be less ⇒ pressure difference ⇒ net force ⇒ acceleration – change in direction ⇒ ball curves in flight.

If the ball is not rotating the flow around the ball is symmetrical and there is no pressure difference to provide lift or curve. There will be turbulence behind the ball that produces a drag force in the direction opposite to the motion of the ball.



NO CURVE
Drag force is opposte to the direction of motion



What is the difference in flight for a tennis ball hit with top spin compared to backspin?

Professional golf drive
Initial speed $v_0 \sim 70$ m.s^{-1}
Angle ~ 6°
Spin $\omega \sim 3500$ rpm
Range ~ 100 m (no Magnus effect)
Range ~ 300 m (Magnus effect)

A golf ball leaves the tee with a speed of about 70 m/s and a backspin of at least 50 rev/s. The Magnus force can be thought of as due to the relative drag on the air on the top and bottom portions of the golf ball: the top portion is moving slower relative to the air around it, so there is less drag on the air that goes over the ball. The boundary layer is relatively thin, and air in the not-too-near region moves rapidly relative to the ball. The bottom portion moves fast relative to the air around it; there is more drag on the air passing by the bottom, and the boundary (turbulent) layer is relatively thick; air in the not-too-near region moves more slowly relative to the ball. The Bernoulli force produces lift. (Alternatively, one could say that the flow lines past the ball are displaced down, so the ball is pushed up.)

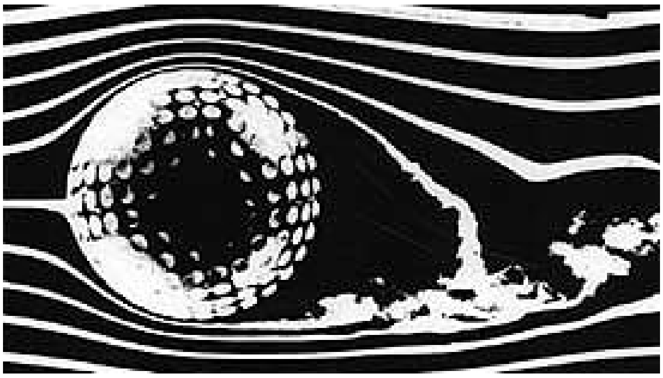
The difficulty comes near the transition region between laminar flow and turbulent flow. At low speeds, the flow around the ball is laminar. As speed is increased, the bottom part tends to go turbulent *first*. But turbulent flow can follow a surface much more easily than laminar flow.

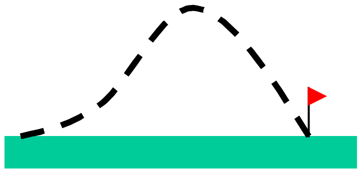
As a result, the (laminar) flow lines around the top break away from the surface sooner than otherwise, and there is a net displacement *up* of the flow lines. The Magnus lift goes *negative*.

The dimples aid the rapid formation of a turbulent boundary layer around the golf ball in flight, giving more lift. Without them, the ball would travel in more of a parabolic trajectory, hitting the ground sooner (and not coming straight down). This was discovered by accident in the early days of golf when golfers noticed that old roughened golf balls went further.

Despite the drag, a dimpled golf ball can even go further in air than it would in vacuum given the same initial velocity and low angle. However, a golf ball shot at 45 degrees and 70 m/s in vacuum would go 500 m to the first bounce, which exceeds all records.

http://math.ucr.edu/home/baez/physics/General/golf.html





The trajectory of a golf ball is not parabolic

Golf ball with backspin (rotating CW) with air stream going from left to right. Note that the air stream is deflected downward with a downward force. The reaction force on the ball is upward. This gives the longer hang time and hence distance carried.

http://www.physlink.com/Education/AskExperts/ae423.cfm

http://www.physics.nwu.edu/classes/2001Spring/135-1/Projects/9/trajectory.html

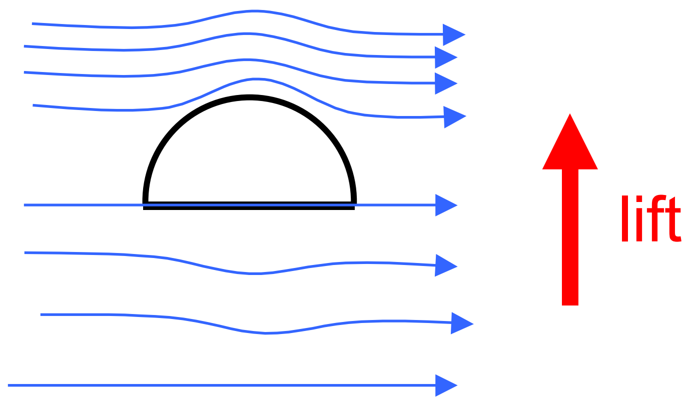
? How can a plane fly?

http://www.amasci.com/wing/rotbal.html

LIFT

For a symmetrical object the flow pattern is symmetrical above and below the object and hence no pressure difference to cause lift.

However, if the object is asymmetrical then the streamlines can crowd together move above the object then below ⇒ increase speed above ⇒ reduced pressure ⇒ lift (Bernoulli's principle)



Aircraft wings are designed to deflect air so that streamlines flow is largely maintained but with the streamlines crowded together above the wing to produce lift.

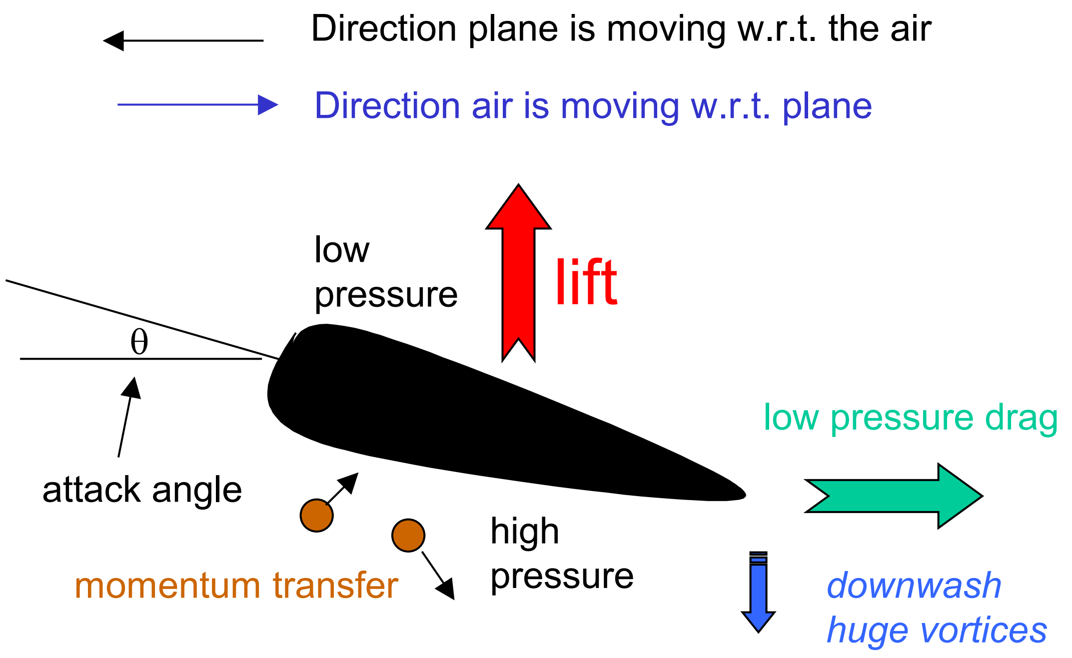
Bernoulli's principle is only one aspect of lift. Wings are usually titled slightly upward so that air striking the bottom is deflected downward. The rebounding air molecules result in an additional upward force on the wing and so turbulence is critical to flight. The moving air at the underside is deflected downward and transfer momentum to the wing. This is how planes fly upside down.

The above treatment is only a simplified model. Another model introduces the concept of circulation. The air induces a circulation of air around the wing because of the viscosity of the air and the creation of a boundary layer (air sticking to wing). This circulation combines with the free air flow to produce a higher speed above the wing than below. Turbulence and viscosity are both necessary to set up the circulation.

Circulation depends upon

- shape of the airfoil
- speed of plane
- orientation of airfoil with respect to the air flow (attack angle)

A plane can fly horizontally, nose up with wing titled at a non zero attack angle. If attack angle too great (> 20°) ⇒ boundary layer tears away from top of wing ⇒ turbulent air ⇒ wing stalls ⇒ lift vanishes ⇒ plane falls.



Another model for flight was illustrated in the picture above. The plane flying through the air produces massive vortices that are "thrown" downward producing the lift by momentum transfer to the plane.