Sports ball aerodynamics

Rod Cross, Physics Department, University of Sydney

The flight of a ball through the air is affected by aerodynamic forces in ways that are not immediately obvious to anyone other than those who have studied the subject for many years. In this report I have attempted to simplify the physics for those who would like a crash course in the subject. I am not an expert in the subject myself, but I have summarised the basic physics using sketches published by the experts themselves.

At the simplest level, the effect of the air on a spherical ball is to slow it down and, in many cases, to exert a sideways force on the ball. The slowing down effect is described by a drag force, F_D, that acts backwards on the ball. The drag force is given by

$$F_D = \frac{1}{2} C_D \rho A v^2 \tag{1}$$

where C_D is called the drag coefficient, $\rho = 1.2$ kg.m^{-3} is the density of air, $A = \pi R^2$ is the cross–sectional area of the ball, R is the ball radius and v is the speed of the ball relative to the air. If the air is at rest, then v is the speed of the ball.

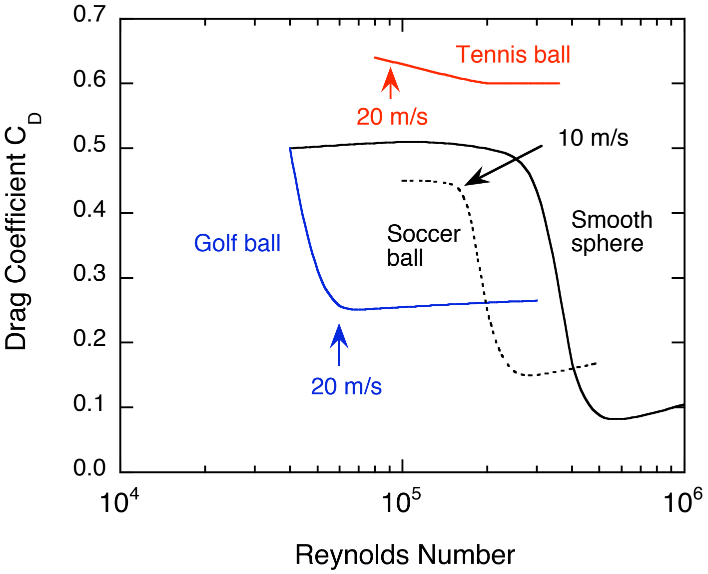


Figure 1: Measured drag coefficients for different non–spinning balls vs Reynolds number.

At high ball speeds, the drag force is commonly equal to or larger than the gravitational force, mg, where m is the mass of the ball. At low ball speeds, C_D is about 0.5 for most balls. At high ball speeds, C_D decreases to about 0.1 if the ball is smooth. If the ball has a rough surface or is physically large then C_D decreases at relatively low speeds, but if the ball is very rough, like a tennis ball, then C_D remains relatively constant at about 0.6 even at high ball speeds.

Graphs of C_D vs the Reynolds number are shown for several different non–spinning balls in Fig. 1. C_D usually increases slightly if the ball is spinning. Reynolds number is dimensionless and is given by $Re = \rho D v/\eta$ where ρ is the air density, D is the ball diameter, v is the ball speed and $\eta = 1.8 \times 10^{-5}$ Poise is the viscosity of air. Re is often expressed in terms of the kinematic viscosity $\nu = \eta/\rho = 1.5 \times 10^{-5}$ m^2/s for air. Fig. 1 is essentially a graph of C_D vs ball speed but the scale depends on the ball diameter. The sudden drop in C_D at ball speeds above 10 or 20 m/s is called the "drag crisis" and represents a change from smooth or laminar flow of air around the ball surface at low speeds, to turbulent flow at high speeds. For a tennis ball, the flow is always turbulent since the surface is quite rough. For smooth surfaces, boundary layer flow becomes turbulent when $Re > 3 \times 10^5$. For rough or dimpled surfaces, the layer can become turbulent when $Re > 4 \times 10^4$ (as indicated by the drop in C_D in Fig. 1).

The slowing down effect of the drag force depends on the mass of the ball and it also depends on the distance travelled by the ball. A heavy ball slows down by a relatively small amount over a short distance, but it will continue to slow down the further it travels. A relatively light ball of the same size, launched at the same speed, will slow down more quickly. The drag force doesn't depend on the mass of the ball, but it does depend on its diameter, its surface roughness and its speed.

A "sideways" force can act to the left or the right or even up or down. In that respect, the sideways force is better classified as a transverse force, meaning that it acts at right angles to the direction of motion of the ball. A transverse force is most commonly due to the Magnus effect which acts when the ball is spinning, but it can also arise if the ball has a raised seam or if the ball is rough on one side and smooth on the other. A transverse force could arise as a result of all three effects acting simultaneously. The transverse force is commonly known as a lift force, F_L, even if it acts to the left or right or downwards, and is usually expressed in the form

$$F_L = \frac{1}{2} C_L \rho A v^2 \tag{2}$$

where C_L is called the lift coefficient.

Trajectory calculations

If C_L and C_D are known, then the trajectory of a ball can be calculated in terms of the force diagram shown in Fig. 2.

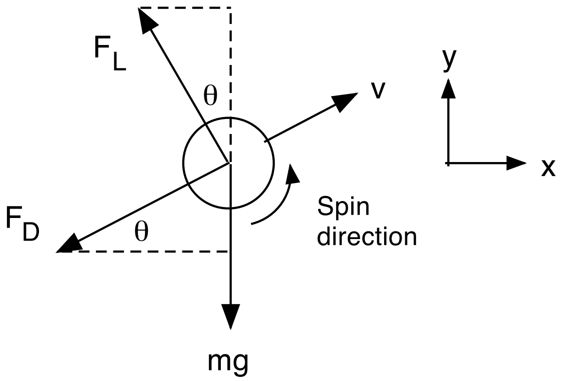


Figure 2: The main forces acting on a ball in flight are the gravitational force, mg, the drag force, F_D and the lift force, F_L. If the ball has backspin then the lift force due to the Magnus effect acts up and to the left, at right angles to the path of the ball.

The equations of motion describing the trajectory of a ball with topspin or backspin are

$$ma_x = -F_D \cos\theta - F_L \sin\theta \tag{3}$$

and

$$ma_y = F_L \cos\theta - F_D \sin\theta - mg \tag{4}$$

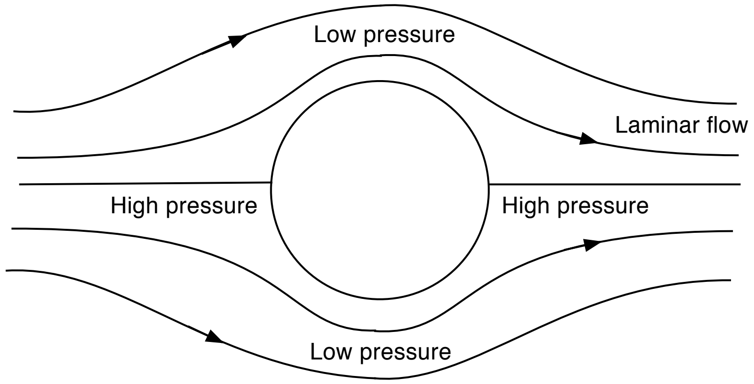
where a_x is the horizontal acceleration and a_y is the vertical acceleration. Equations (3) and (4) can be solved numerically for any given launch speed and launch angle to determine the trajectory in the x-y plane. If the ball has sidespin then the lift force will act in the z direction, in which case motion in the z direction can be determined separately in an analogous manner. A ball launched with backspin will fall more slowly to the ground than a ball launched without spin, and will therefore travel further if it is launched at the same speed and angle. For that reason, golf balls are usually struck with backspin. If the ball spins fast enough, and is launched fast enough, the lift force can be greater than the gravitational force in which case the ball will curve upwards rather than downwards at the start of its flight. Tennis players like to hit the ball with topspin so that the ball curves down rapidly onto the court after it crosses the net.

Origin of the drag force

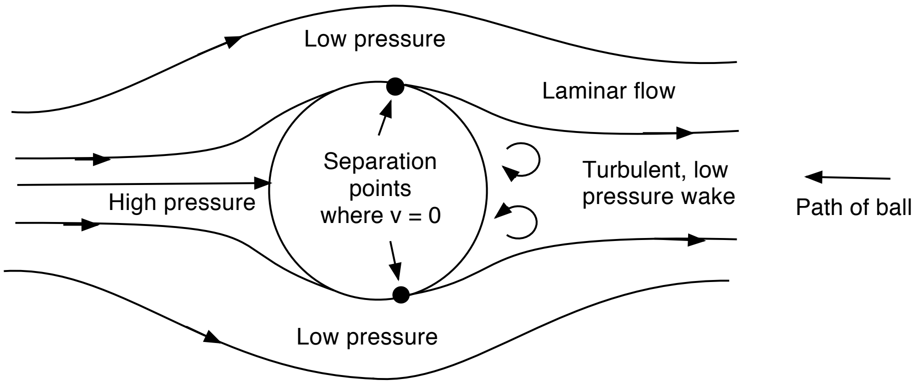
The drag force arises because the ball has to push its way through the air, and the air exerts an equal and opposite force on the ball. The details are more complicated than one might expect, as indicated in Fig. 3. At very low speeds, air flows smoothly around the ball from the front to the back. Smooth flow is classified as laminar flow. In an ideal situation there is no friction between the air and the ball, the pressure at the front of the ball is the same as the pressure at the rear of the ball, so there is no drag force. In reality, air flowing over the surface of the ball is slowed down by friction with the surface of the ball until it comes to rest at a point known as the separation point. As a result, the flow of air separates from the ball at the separation point rather than following the surface around to the rear of the ball. The air pressure drops in a region at the back of the ball known as the wake, causing air outside the wake to flow back into the rear side of the ball in a turbulent manner. The details are too complicated to describe here, but the net result is that the force on the front of the ball is larger than the force at the back of the ball, so the ball experiences a backwards drag force that increases as the ball speed increases or, for a stationary ball, as the incoming air speed increases.

If the surface of the ball is rough, or if it is dimpled, then the flow of air around the surface can be become turbulent well before the air speed drops to zero. In that case, air near the surface mixes with air further away from the surface that is moving faster than air right at the surface. The speed of the air at the surface is therefore increased by the turbulence, so the surface air takes longer to slow to a stop, and the separation point moves closer to the rear side of the ball. The low pressure wake is therefore narrower, so the force of that low pressure region on the ball is decreased and the force of the higher pressure region outside the wake is increased. As a result, the drag force is reduced compared with that on a smooth ball.

(a) Ideal frictionless flow around a smooth sphere : zero drag force



(b) Viscous flow around a smooth sphere : finite drag force



(c) Viscous flow around a golf ball : low drag force

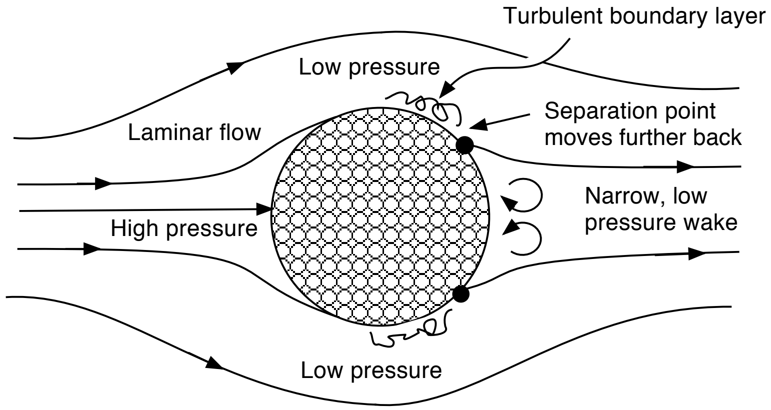


Figure 3: Air flow around a ball travelling to the left. The ball is not spinning. For convenience, it is assumed that the ball is at rest and the air flows from left to right around the ball. That is how balls are tested in wind tunnels.

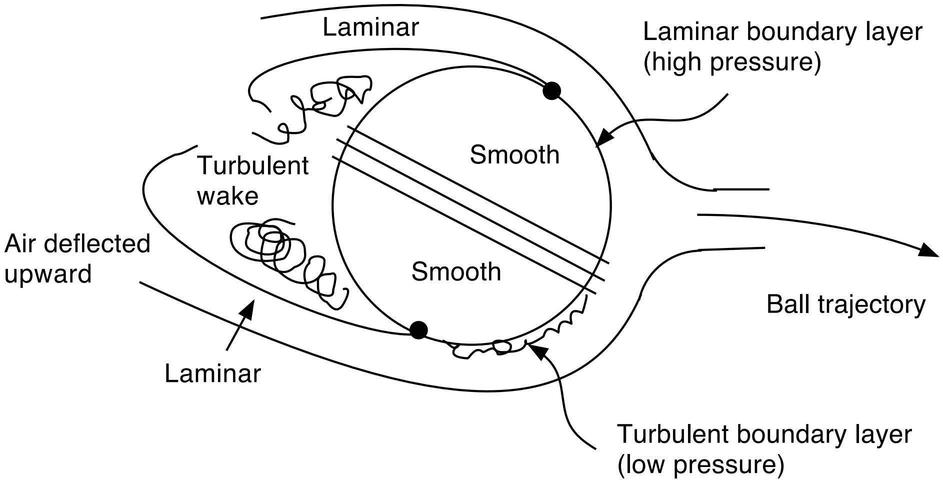
Swing of a cricket ball

The flight of a cricket ball is complicated by the facts that the ball has a seam and that one side of the ball is rougher than the other side. Both sides are smooth when the ball is new, but players polish one side during the game and allow the other side to roughen up during play. The ball is bowled with backspin in order to keep the seam aligned at an angle of about 20 degrees to the flight path, since that angle gives the maximum left to right side force on the ball. When the ball is new, the ball curves to the right if the seam points to the right, as indicated in Fig. 4(a). However, if the ball is bowled at a speed greater than about 85 mph, then the ball curves to the left, as shown in Fig. 4(b). The latter curvature is known as reverse swing.

The ball can be made to swing to the left at low speed simply by pointing the seam to the left and by changing the bowling action. Most bowlers prefer one way or the other since it is easier not to change the bowling action. In that case, the swing direction is determined by the ball speed. However, reverse swing can occur at lower ball speeds if one side of the ball is rougher than the other side, as shown in Fig. 5. Furthermore, reverse swing can then occur even if the seam points straight to the batter, as shown in Fig. 6.

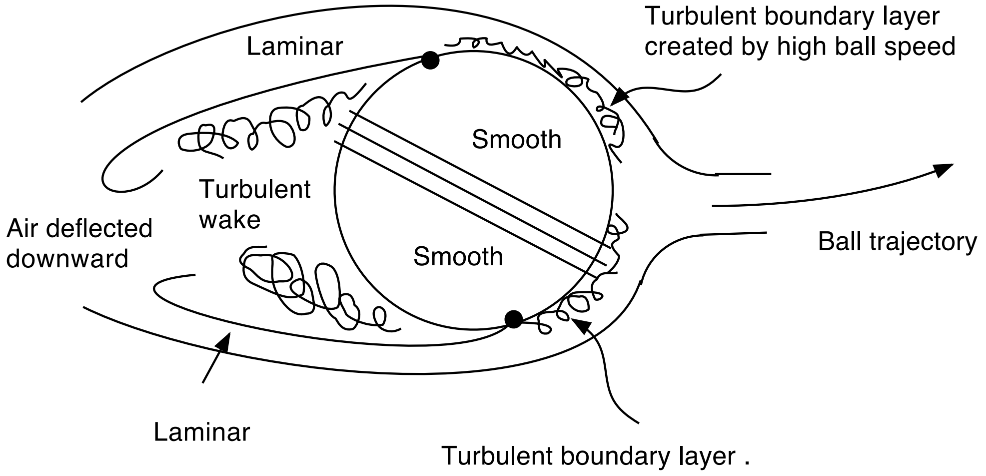
The physics behind the various swing types lies in the way that the air travels around the surface of the ball. At low ball speeds, the flow is laminar, unless the air encounters a seam or a rough patch on the ball, in which case the flow becomes turbulent. As a result, the separation point can move either closer to the front of the ball or further back to the rear side. If the ball deflects air to the left, then the air exerts an equal and opposite force on the ball to the right. The air is deflected in a direction more or less tangential to the ball at the separation point, as shown in Figs. 3 to 6, and then flows back toward the middle of the ball around the wake behind the ball. Inspection of those diagrams reveals a general rule of thumb, that the ball deflects to the side where the separation point is further back toward the rear of the ball.

(a) Swing bowling with new ball (both sides smooth): bird's eye view.



Ball has backspin to keep the seam aligned at about 20 degrees to the air flow.
Black dots show separation points. Separation is delayed by turbulence.

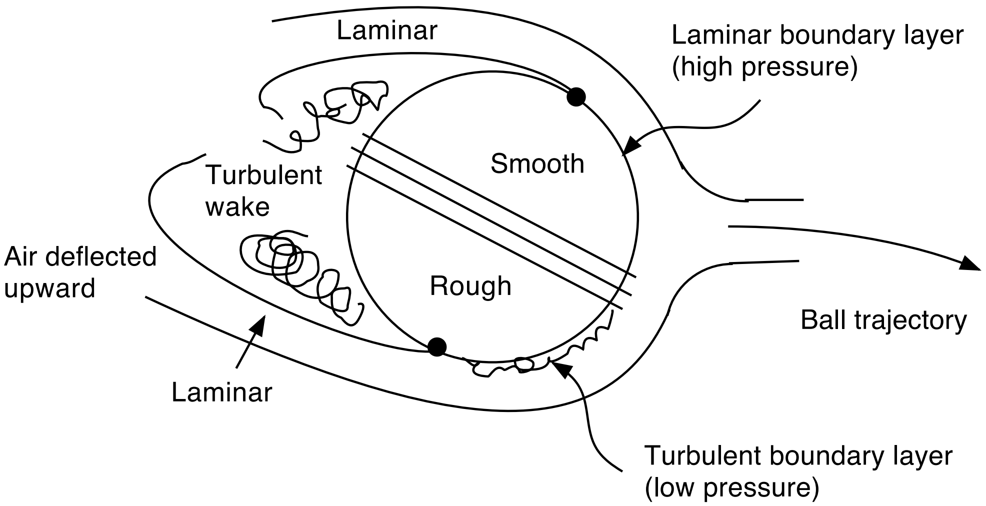
(b) Reverse swing at high ball speeds (both sides smooth): bird's eye view.



Ball has backspin to keep the seam aligned at about 20 degrees to the air flow.
Bottom separation point moves toward front of ball at high ball speeds. Top
separation point moves toward rear of ball due to onset of turbulence.

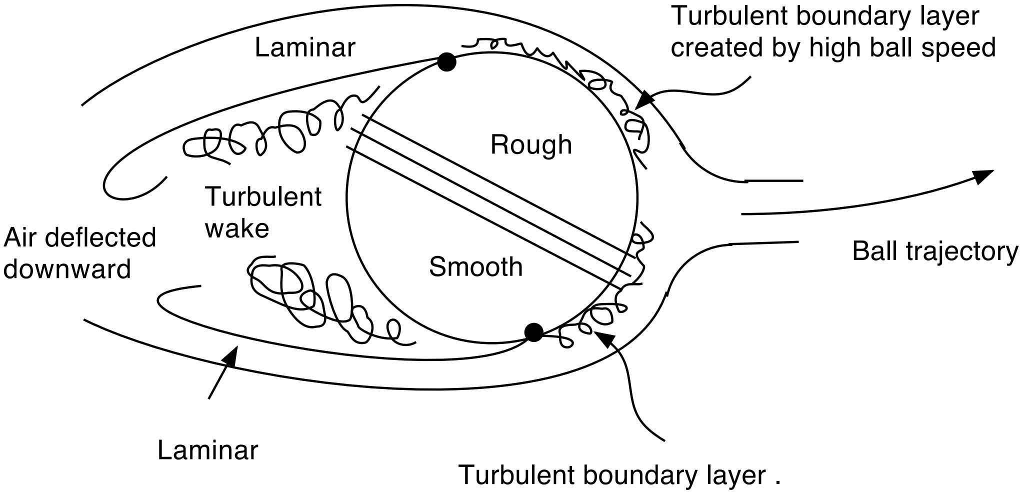
Figure 4: Air flow around a new cricket ball travelling to the right.

(a) Swing bowling with old ball (one side smooth): bird's eye view.



Ball has backspin to keep the seam aligned at about 20 degrees to the air flow.
Black dots show separation points. Separation is delayed by turbulence.

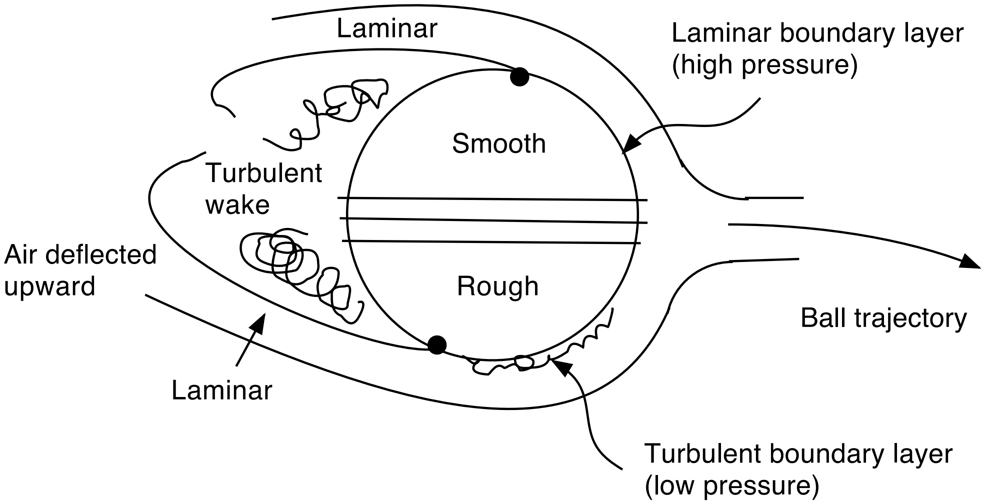
(b) Reverse swing (one side smooth): bird's eye view.



Ball has backspin to keep the seam aligned at about 20 degrees to the air flow.
The ball is turned over compared with conventional swing but the seam
alignment is the same. There is no change needed in the bowling action.

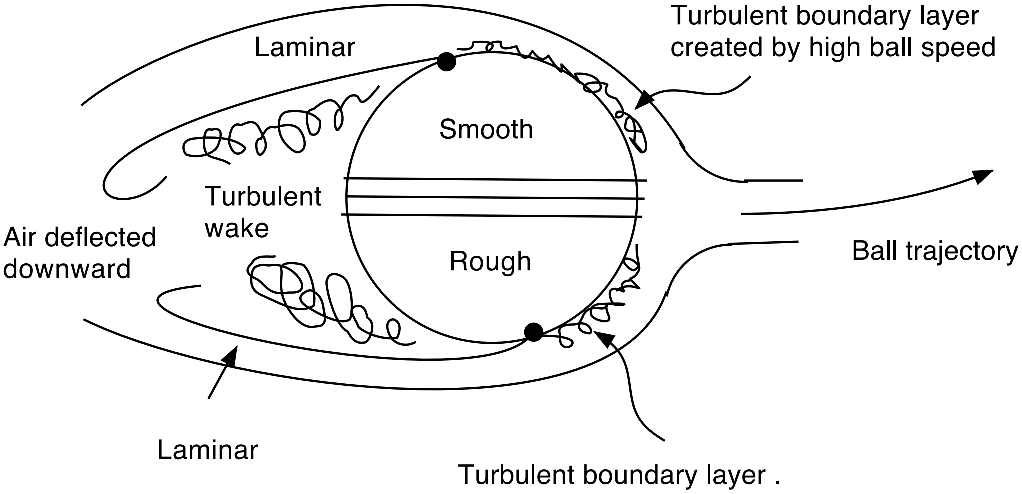
Figure 5: Air flow around an old cricket ball travelling to the right.

(a) Contrast swing- straight seam: bird's eye view.



Ball has backspin to keep the seam aligned parallel to the air flow.
Black dots show separation points. Separation is delayed by turbulence.

(b) Reverse contrast swing at high ball speed: bird's eye view.

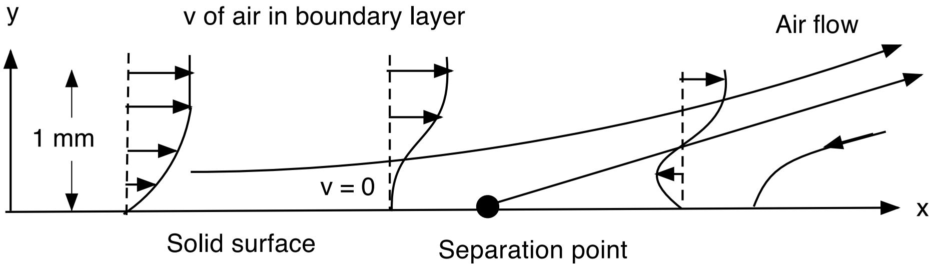


Ball has backspin to keep the seam aligned parallel to the air flow. Separation occurs sooner on the rough side. A similar result can be achieved at low ball speeds simply by reversing the smooth and rough sides of the ball.

Figure 6: Air flow around an old cricket ball when the seam is straight.

Boundary layer and separation point

The following diagram illustrates the nature of viscous air flow in a boundary layer over a flat surface. The layer is typically about 1 mm thick. The velocity $v = 0$ right at the surface. v increases away from the surface (in the y direction) and decreases along the surface (in the x direction). After a sufficient distance, the flow separates from the surface if $dv/dy = 0$ at the surface and then recirculates with negative velocity back toward the surface.



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