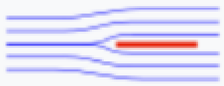
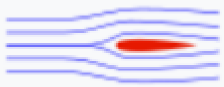
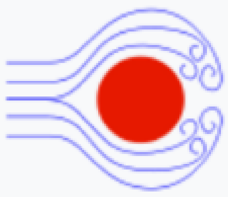
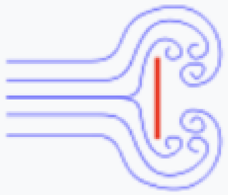
# Motion of a Ball in Air

When golf originated in Scotland, players quickly learned that dented balls sometimes fly faster. Thus, designers put *rigid* dimples on the balls. The rigid dimples on the golf ball made the ball go further. There is a reason for this, but it requires an understanding of two competing types of drag.

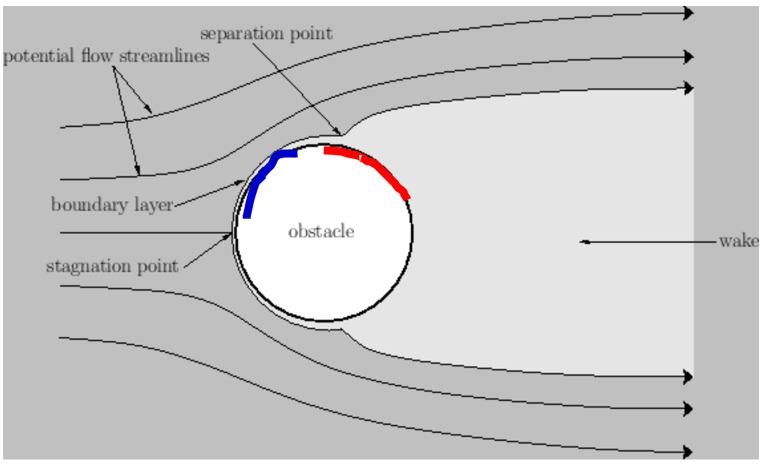
**Form drag**: One could *qualitatively* assert that *form* drag operates on the front of the object as it "pushes" its way through the medium. As an object becomes more bluff, and exposes more area to the incoming stream, the form drag increases as seen in the first column.

**Skin Friction drag:** One could *qualitatively* assert that *skin friction* drag arises from "sliding through" a medium. Friction drag operates on the sides of object as it "slides." The greater the area of the object exposed to the fluid flowing past, the more friction as shown in the second column. One can see that as the object becomes more bluff, with sides less exposed to the fluid, the skin *friction* reduces.

| Shape and flow | Form Drag | Skin friction |
|---|---|---|
|  | 0% | 100% |
|  | ~10% | ~90% |
|  | ~90% | ~10% |
|  | 100% | 0% |

## Boundary Layer, Separation and Turbulence

As the fluid moves past the object, fluid molecules adjacent to the surface stick to the surface. Since we are observers on the ball, these fluid molecules have zero velocity. We call this region the boundary layer. The blue line in the figure below is a boundary layer of fluid that sticks to the ball.



These molecules in this boundary layer collide with incoming particles just slightly above, slowing those down and inducing the flow to rotate (the molecules to tumble over each other). These molecules, in turn, also slow down the flow just above them. Higher above the surface the molecules are more affected by the fast flowing air, and not by the ball.

This effectively creates a thin boundary layer of fluid near the surface in which the velocity changes from zero (at the surface of the ball) to the free stream value (away from the surface). Engineers call this layer the boundary layer because it occurs on the boundary of the body. One can observe this region on the blue surface area of the ball.

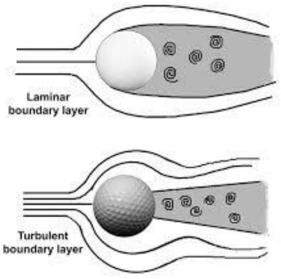
Suppose, however, the air flows very fast over the surface. In this case, the strength of the “flow” reaches down into the boundary later and ensures that all particles strip off and flow. Thus, the fluid velocity within the boundary layer no longer stays attached to the ball. In other words, as the air flows around the ball, it does not want to stick to the surface. It wants to stick to the fast moving flow. Thus, the flow lifts away creating a large wake in the rear. See the red region in the figure, above.

Engineers observe randomly churning eddies in the wake region.

These spiraling vortices develop from the *re-circulating* regions where the boundary layer separates. They exhibit as a rotating flow. This rotating flow has a centripetal component to curve fluid particle trajectories inward, locally, in each vortex region.

Since the particles have a centripetal acceleration toward the center of a vortex, the pressure decreases toward the center of these spirals in the rear. Therefore, the center of a vortex must have a lower pressure than the surroundings. The large number of vortices effectively reduces the overall pressure in the wake.

Thus, the larger the wake region, the greater the pull toward the center of each vortex.



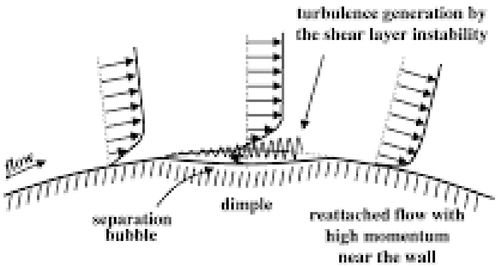

In the second figure above, there is less rotational flows and there is less pressure.

In the first figure above, the larger wake region will pull back on the ball with a greater drag.

If one can minimize the amount of randomly churning eddies in the wake—the effective vacuum-like region (admittedly, a slight exaggeration, but sufficiently descriptive) pulling back on the ball—form drag—would reduce.

**Golf Balls**

Golf balls have rigid dimples that change how the air flows. As the air passes over the dimples shown below, it detaches, and then reattaches as it encounters the dips and peaks of the dimples. This *relatively more attached flow* induces a smaller wake and, thus, a smaller low-pressure “vacuum-like” region, and, thus, less pullback on the ball, and finally, less drag.




With less pull-back drag from the wake region, the golf ball can fly further.

This type of dimple-induced turbulence does increase skin friction drag, but reduces form drag. For a golf ball, the decrease in form drag is greater than the increase in skin friction drag. These competing effects are intricate.

**Tennis Balls**

Felt-covered tennis balls originated in the late 1800s, before Prandtl laid the groundwork for describing boundary layers. Thus, it is unlikely that the purpose of the fuzz was about aerodynamics; it was more about friction between the ball and racket. Friction with the racket enabled more spin (which is yet another aspect). Despite this, the fuzz does have an aerodynamic role, but one more complicated than the dimples on tennis balls.

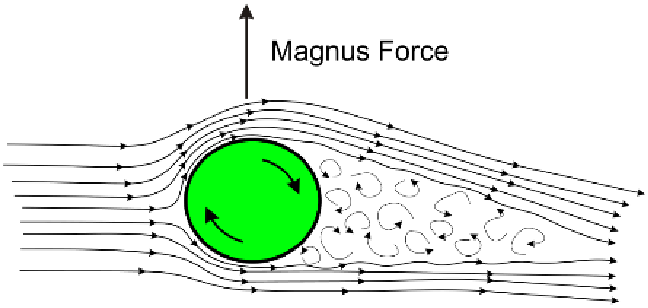
The fuzz is going to do one thing that rigid dimples will not: individual threads of fuzz are going to flap in the wind. This will increase friction drag. The increase in skin friction drag due to flapping outweighs the decrease in form drag for a tennis ball.

However, now the situation now gets far more complicated. It is possible that once the tennis ball is flying fast enough, the fuzz does not flap. Then, one can model it like a rough rigid structure on the surface of the ball. In these cases, as with the case of golf balls, this can make the ball go even faster, returning us to the logic of rigid dimples.

**Magnus Force**

Three forces act on the golf ball when it is flying in the air. Two of them are now clear: gravity and drag (skin drag and form drag). One force that also appears is due to Magnus effect and called the Magnus force.

As the ball travels through the air, consider that it is spinning. Notice that there is a relatively fast flowing air at the top of the ball due to how the ball pulls the air as it rotates.



Some often rationalize the cause of this effect using Bernoulli's equation. Some will learn by studying fluid mechanics that fast flowing fluids exhibit a lower pressure.  Indeed, it appears reasonable to apply this principle here, but it represents a misunderstanding of the effect of Bernoulli's equation. Bernoulli's equation does not *cause* anything. It is a calculation scheme. It lets one calculate the pressure when one knows the velocity. It has restrictions in its use. It is only valid along a streamline. It is only valid for inviscid flow (fluid with zero viscosity). It is only valid for incompressible flow (constant density fluid).  Thus, we cannot rationalize this phenomena with Bernoulli's equation.

A more grounded, yet conceptual, understanding of the Magnus Effect comes from Newton's third law: the deflective force on the body is a reaction to the deflection that the body imposes on the air-flow.  The body "pushes" the air in one direction, and the air pushes the body in the other direction.  Essentially, in the figure, the spinning ball pulls the fluid down in the near-rear. A free body diagram reduces this to action/reaction: the fluid pulls up on the ball in the near-front and causes the ball to curve.

**Summary**

Let us summarize as we contemplate this complex array of phenomena.  The dimples on a golf ball increase friction drag, but reduce form drag.  Fuzz on a tennis balls increases skin friction and slows down the ball.  However, if the tennis ball is already fast enough, the fuzz can compress and the ball speeds up due to reduced form drag.   Finally, an increase in turbulence delays separation (we are not discussing the boundary layer); the air flows faster, and this then enhances the Magnus effect, but only when the ball is spinning.

Before we continue, note that the qualitative discussion on the lift and drag on a ball does not apply to that for an airfoil, like a wing.  The airfoil is not symmetric across its longitudinal axis.  The air at the top flows faster along streamlines, inducing a lower pressure due to Bernoulli's equation.  This induces the lift.  When the flow separates from the airfoil, there is no additional lift.