quick study

Power and spin in the beautiful game

John Eric Goff

After a ball leaves a soccer player's foot, surface roughness and asymmetric air forces contribute to some jaw-dropping trajectories.

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It is World Cup time, and people all over the planet have their eyes on South Africa. For a major US event like the annual Super Bowl, viewership is perhaps 100 million. That number jumps by an order of magnitude when the World Cup arrives every four years. Those who tune in will see not only exciting soccer (called football in most countries) but also fascinating physics in action.

Boundary layer and drag

Professional soccer goalies allow at most only a few goals in a game. Free kicks and corner kicks, though, represent relatively good scoring opportunities and so are particularly exciting. Some fans may especially admire the power delivered by the Netherlands' Robin van Persie; others may marvel at the curves imparted by England's Steven Gerrard. Either way, physics reveals why the ball moves the way it does.

As a soccer ball moves through air, it feels a force due to pressure differences and to interactions between the viscous air and the ball's surface. The viscous forces are important in the boundary layer, a concept introduced by Ludwig Prandtl at the turn of the 20th century. In that region, near the surface of the ball, the air speed relative to the ball's surface rises from zero at the surface to nearly its free-stream value (see the article by John D. Anderson Jr in PHYSICS TODAY, December 2005, page 42). The boundary layer is thinnest on the front of the ball, which faces the oncoming air, and thicker farther back. Eventually it separates from the ball altogether and leaves a complex flow pattern with swirling eddies in its wake. Much of the wonderment of soccer trajectories depends on where the boundary layer separates.

Perhaps the most important parameter in fluid dynamics is the Reynolds number, $Re = VD/\nu$, with V the ball's center-of-mass speed relative to the air and D the ball's diameter; the kinematic viscosity ν is the ratio of air's viscosity to its density ρ. By applying Newton's second law to a viscous fluid moving around an object, one obtains the Navier–Stokes equation. That equation can be put in dimensionless form if distance is scaled by D and time is scaled by D/V; the result is an equation with a single parameter, Re, which determines the fluid's dynamics. Engineers use that result when they test with scale models. They could, for example, study a ball with half the diameter of a soccer ball in a wind tunnel that simulates the ball moving at twice the normal speed. As long as the model has the same geometry and surface as the standard ball, they should observe the same fluid phenomena, because halving the diameter while doubling the speed maintains the same Re.

The air's pressure and viscous interactions with the ball give rise to the drag force, which points opposite to the ball's velocity. The magnitude of the force is $F_D = (\rho V^2/2)\cdot A\cdot C_D$, with A the ball's cross-sectional area and C_D the dimensionless drag coefficient, which depends on Re and the spin rate. I'll discuss spin in the next section; for now, consider a nonrotat-

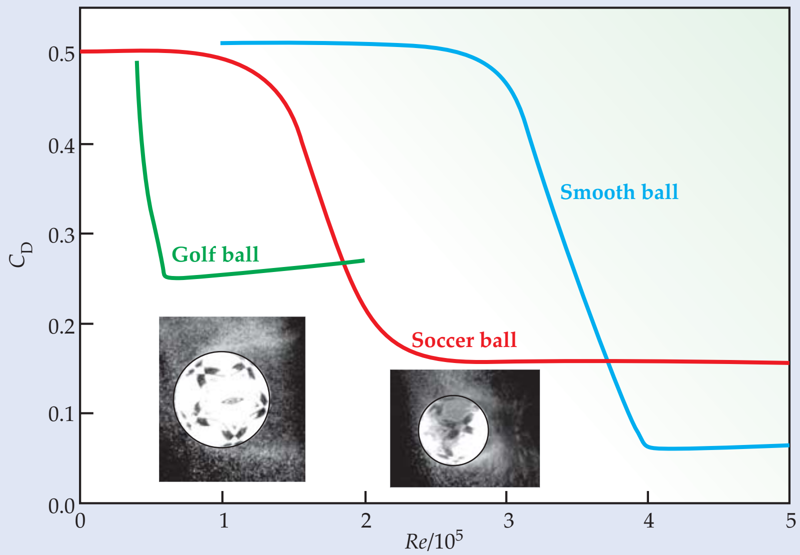

Figure 1. The drag crisis. In this plot of drag coefficient (C_D) as a function of Reynolds number (Re), the rapid drop in C_D, the drag crisis, indicates the transition from laminar to turbulent air flow. The crisis is precipitated when the surface of the ball is rough. For a soccer ball, $Re/10^5 \approx V/(7\text{ m/s}) \approx V/(16\text{ mph})$, where V is the speed of the ball. In the two insets, illuminated dust reveals the separation of the boundary layer from a soccer ball moving through air. The left image corresponds to a Reynolds number of 1.1×10^5 and laminar flow. For the right image, $Re = 2.7 \times 10^5$ and flow is turbulent; note that the boundary-layer separation is farther back in that image. The trajectory of a well-struck free kick is always in the turbulent regime.

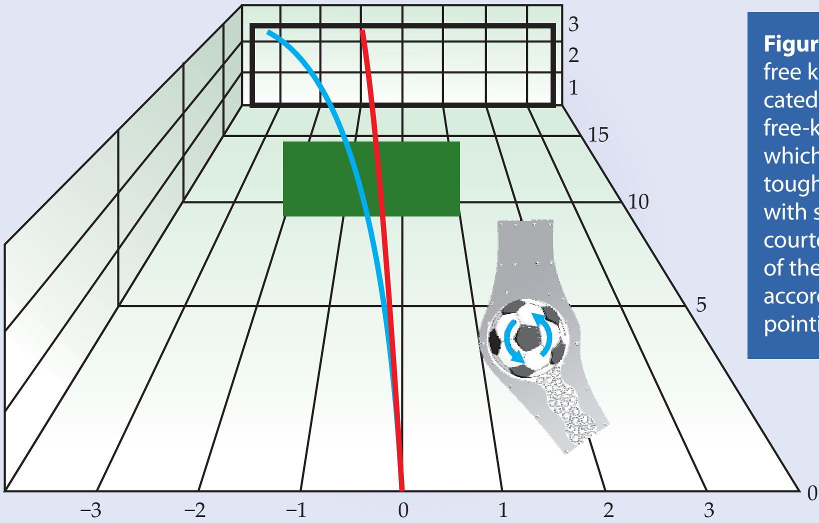

Figure 2. Gooooal! When a soccer player is awarded a free kick, the defenders assemble in a wall, as indicated by the green rectangle. This plot shows two free-kick trajectories that clear the wall: the red curve, which corresponds to a ball without spin, and the tougher-to-intercept blue curve, representing a ball with sidespin. All distances are in meters. The inset, courtesy of Kenneth Wright, shows an overhead view of the ball, which deflects the air to the right. Thus, in accord with Newton's third law, the air exerts a left-pointing force on the ball.

ing soccer ball moving through the air. Air flow around the ball at low speeds is laminar (smooth rather than turbulent). At high speeds, air flow is turbulent, and the boundary layer separates farther back than for laminar flow; as a result, C_D is smaller for the turbulent separation.

Figure 1 shows C_D as a function of *Re* for three sports balls. Note the precipitous drop in C_D, known as the drag crisis, that indicates the transition from laminar to turbulent flow. Surface roughness induces the transition to turbulence at smaller *Re*. So, for example, a dimple-covered golf ball has its drag crisis at smaller *Re* than a soccer ball, but the soccer ball's drag crisis is at a smaller *Re* than for a smooth ball such as a racquetball; a golf ball without dimples could not travel nearly as far as a normal golf ball. Some experimental data show that beyond the drag crisis, C_D rises slightly for soccer balls and more steeply for rougher balls. A baseball has a C_D versus *Re* curve similar to that of a soccer ball for *Re* up to about 2×10^5; not much data exist for baseballs beyond the drag crisis.

For soccer balls, the drag crisis sets in when the speed is about 12 m/s, comparable to that of a medium-range pass. A van Persie free kick leaves his shoe with $Re \approx 5 \times 10^5$ and enters the goal with $Re \approx 3 \times 10^5$; for the entire trajectory of the ball, *Re* is above the crisis value. Initially, the drag force on the ball is about 15% greater than the ball's weight. For a major-league fastball, $Re \approx 2 \times 10^5$ and the drag force is comparable to the weight of the ball. A golf ball launched at 70 m/s has $Re \approx 2 \times 10^5$ and experiences a drag force more than twice its weight. The common introductory physics simplification of ignoring air resistance is certainly not applicable to the study of sports projectiles.

A banana kick with whipped air

For an effective free kick, a soccer player like Gerrard wants to give the ball a large initial speed so that the goalie has little time to react. He also wants to spin the ball so that it curves past the goalie. Those are competing needs: The large translational speed requires a kick through the ball's center, but a large rotational speed necessitates an off-center kick. A good Gerrard kick has an initial sidespin of some 600 rpm. By comparison, a major-league curveball spins at a rate of about 2000 rpm and a golf ball leaving the tee might have a backspin of 2500 rpm or more, in part thanks to the golf club's grooved and tilted face.

A rotating ball with angular velocity $\boldsymbol{\omega}$ whips air behind it. As the inset to figure 2 shows, an important feature of that process is that the boundary layer separates farther back on the side of the ball that rotates in the direction opposite to the center-of-mass velocity $\mathbf{V}$. Because of that asymmetry, the air exerts a force on the ball—called the Magnus force in honor of Heinrich Gustav Magnus—in the direction of $\boldsymbol{\omega} \times \mathbf{V}$. A similar phenomenon occurs at sea, when a boat's rudder deflects water asymmetrically behind a boat executing a turn. The Magnus force acts in addition to the drag force. Of course, the air exerts only a single force on the ball; how that force is split into components is up to the scientist.

Figure 2 shows a Gerrard-like free kick. The right-footed Gerrard strikes the ball from a spot about 20 m from the goal. A wall of defenders shifted toward Gerrard's left hopes to be "lucky" enough to be hit by the ball; the goalie guards Gerrard's right half of the goal. Gerrard aims to put the ball in the upper-left portion of the goal. An agile goalie can often stop a ball kicked with no spin but will have a much tougher time with Gerrard's spinning ball, whose banana-shaped trajectory not only curves as shown in the figure but actually dips a bit. The initial magnitude of the Magnus force on a free kick is comparable to the ball's weight. Likewise, a golf ball just driven from the tee experiences a Magnus force comparable to its weight. For a curveball, the initial Magnus force is relatively smaller, about a quarter of the baseball's weight.

To study the aerodynamics of sports balls, researchers use wind tunnels, sophisticated computational fluid dynamics programs, and computation-based trajectory analysis. My colleagues and I have studied the 32-panel soccer ball with its well-known pentagons-and-hexagons pattern and the Adidas Teamgeist ball, with its 14 thermally bonded panels, that was used for the 2006 World Cup. Our tests failed to discern significant differences in C_D over a wide range of *Re*, but they do suggest that the Magnus force on the Teamgeist ball is slightly larger than on the 32-panel ball. This year's World Cup is using the Adidas Jabulani ball, which has eight thermally bonded panels and grooves on its surface. A great deal of rich physics lies behind those spinning sports balls, whose trajectories will cause elation in one country and anguish in so many others.

Additional resources

▶ J. E. Goff, *Gold Medal Physics: The Science of Sports*, Johns Hopkins U. Press, Baltimore, MD (2010), chap. 7.
▶ J. Wesson, *The Science of Soccer*, IOP, Bristol, UK (2002).
▶ J. E. Goff, M. J. Carré, "Soccer Ball Lift Coefficients via Trajectory Analysis," *Eur. J. Phys.* **31**, 775 (2010).
▶ J. E. Goff, M. J. Carré, "Trajectory Analysis of a Soccer Ball," *Am. J. Phys.* **77**, 1020 (2009).
▶ B. G. Cook, J. E. Goff, "Parameter Space for Successful Soccer Kicks," *Eur. J. Phys.* **27**, 865 (2006). ■