

Fluid Mechanics

Hamill & Knutzen (Ch 10 [small section]), Hay (Ch. 7), Hay & Ried (Ch. 13), Kreighbaum & Barthels (Module H, Ch 11 & 12) or Hall (Ch. 15)

Special thanks to Dr. Len W. Brownlie
(Aerosports Research)

Dr. Brownlie taught a special topics course in this area
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Fluids

- Fluid (gases and liquids)
- Solids: molecules provide specific shape
- **Liquids**: deformable - take shape of container but incompressible
- **Gases**: deformable and compressible
- Fluid refers to a gas or liquid which is deformable
- A fluid is any substance that tends to flow (continuously deform) when acted upon by a shear force.
- Fluid resistance can be negligible (weight lifting) or considerable (cycling), resistive (running) or propulsive (rowing).

Fluid Dynamics



Hydrodynamics

Aerodynamics

Is it important?



- **Yes! For example:**
- **Lance Armstrong won the 2003 Tour de France in 83 hours 41 minutes 12 seconds - 61 seconds or 0.02% better than Jan Ulrich**

Pressure

- When a fluid moves over or through an object, it gives small pushes on the surface of the object. These pushes, over the entire surface, are defined as pressure and are **measured as force per unit area (square inches, square meters)**. In metric units, pressure is measured in Newtons per square meter. In the English system, pressure is usually measured in pounds per square inch. Example: The atmosphere (air) presses on your skin at 14.7 pounds per square inch (psi).
- Pressure can be powerful. A small pressure, spread over a very large area, can add up to be a very large force. Air pressure decreases as altitude increases; pressure also decreases when the speed of the fluid (air, water) increases (Bernoulli) .

Density

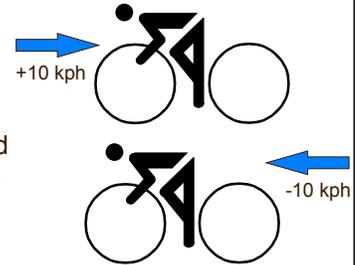
- **Density** is a measure of mass (the amount of molecules) per unit volume.
- Density of fluid (volume) is measured in lbm/ft³ or kg/m³. SYMBOL: RHO " ρ "
- Fluids with a lot of molecules tightly packed together have high densities; ones with fewer molecules have lower densities. Water has a much higher density than air.
- **Density** is also used to define whether a fluid is incompressible or compressible. If the density of the fluid is fixed (constant), the fluid is incompressible; neither the mass or the volume can change. **Water is an incompressible fluid.** The amount of volume and mass will stay the same, even under pressure.
- Gases (like air), are compressible; they expand to fill a new larger volume. The mass doesn't change, but the volume increases, so the density of the gas decreases in the new volume.

Viscosity (η or μ or ν)

- **Viscosity** (eta - “ η ” or mu “ μ ” or nu “ ν ”) is a measure of how much a fluid will resist flowing. e.g. honey vs. water.
- Two quantities: viscosity and kinematic viscosity (do not worry about distinguishing between them, nor should you worry about the units)
- It can be thought of as the effect of friction in a fluid
- **Friction** (sometimes called skin friction) is a resistance to motion created by two objects rubbing against one another
- When a fluid travels over an object, The amount of friction is determined by:
 - the viscosity of the fluid; and
 - the smoothness of the surface of the object
- <http://atlas.geo.cornell.edu/education/student/viscosity.html>

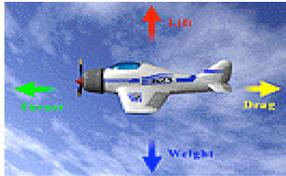
Relative Velocity

If both cyclists were traveling at -40 kph, what would the relative velocity of the fluid moving past them be?



Forces on a body moving through the air

- **Weight** - downward force = mg
- **Propulsive thrust** - ignored here (already covered)
- **Lift** - discussed later; counteracts weight
- **Drag** - the resistive force which slows the forward motion of an object



Definition:

What is drag force?

$$F_d = \frac{1}{2} \cdot \rho \cdot V^2 \cdot A_p \cdot C_d$$

- F_d = drag force in gm or Newtons
- ρ = air density ($\text{kg} \cdot \text{m}^{-3}$)
- V = velocity ($\text{m} \cdot \text{s}^{-1}$)
- A_p = athlete's frontal area (m^2)
- C_d = drag coefficient (an index of how smooth and streamlined the object is)

Aerodynamic / Hydrodynamic Drag

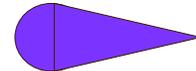
There are 4 types of drag:

- **Friction drag or skin friction drag**, is the force created by surface roughness. Swimmers shave their bodies to reduce friction drag (improved “feel” for the water?).
- **Form or Pressure drag** is affected by the shape of the body. A smooth, streamlined shape will generate less form drag than a blunted or flat body. How much form drag an object will have is determined by its C_d
- **Induced drag** or drag due to lift is a small amount of excess (lift) force generated in the opposite direction of the lift force along a wing. This force slows the forward motion of the airplane
- **Wave drag** - WILL DISCUSS IN SWIMMING SECTION; NOT IMPORTANT AT SUBSONIC SPEEDS

Form (Pressure) Drag



Despite the same cross-sectional area, the shape below would experience approximately 4% of the drag experienced by the rectangle.



Drag Coefficient of Various Objects

- Pigeon: 0.1
- Vulture: 0.06
- Smooth Sphere : 1.0 to 0.3
- Brick: 2.1
- Honda Insight 0.15
- Runner: 0.8



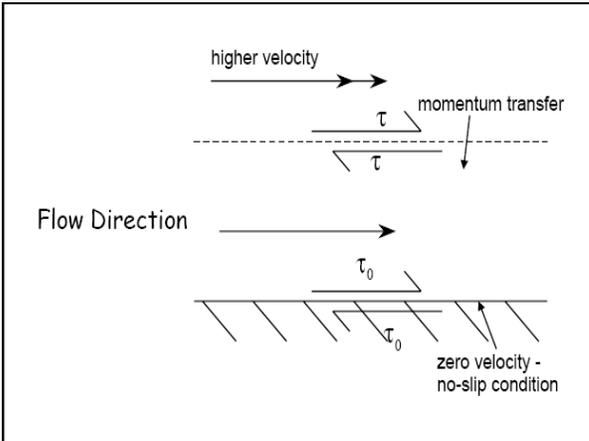
Aerodynamic Drag

$$F_d = \frac{1}{2} \rho \cdot V^2 \cdot A_p \cdot C_d$$

- as ρ decreases, drag decreases
- What is the effect on sprint times of racing at Mexico City (elev. 2,300m)?
- ρ is about 23% lower than at sea level
- sprint times reduced about 1.7% (MacFarland 1986)
- What is the effect on bike time trial times of a reduction in frontal area (A_p)?
- adoption of a full crouch vs. upright position will save a rider 3 minutes (6%) in a 40 km TT (Kyle 1986)

Boundary Layer

- Fluid flow over an object results in a velocity gradient
- By the "Law of the Wall" the thin layer of air touching the object has a velocity of 0. The next layer up has a higher velocity and the next layer up has an even higher velocity etc.
- The distance from the original surface to the layer of the flow traveling at the original velocity is called the **boundary layer thickness**.

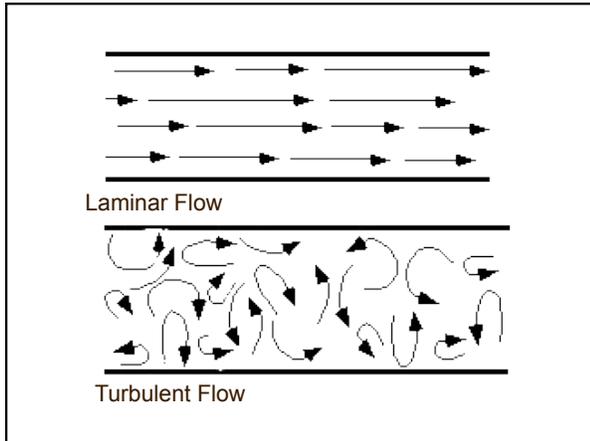


Boundary Layer

- The thickness of the BL depends on:
 1. the shape of the object - thin short objects have smaller BL long objects give the BL space over which to grow
 2. the roughness of the surface - smooth surfaces have less friction and a smaller BL.
 3. the velocity of the fluid - very slow moving fluids have very orderly flow patterns termed LAMINAR

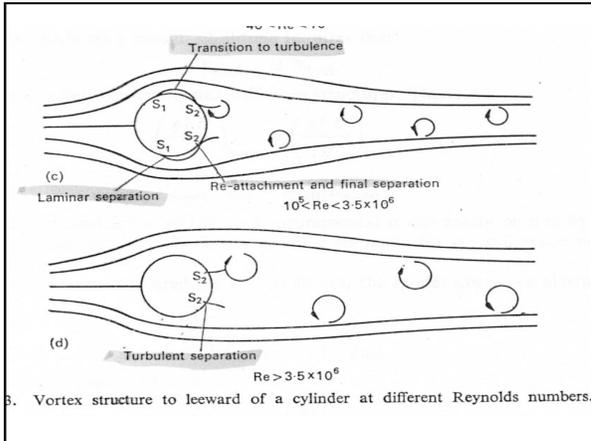
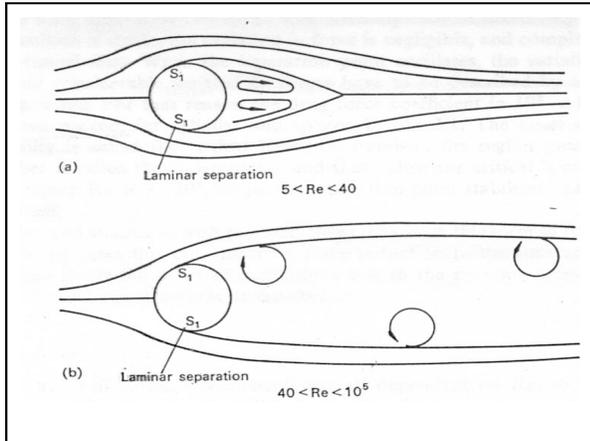
Turbulent Boundary Layer

- "Nature moves towards disorder"- think of smoke rising from a candle
- As the various layers mix and swirl over one another, the BL becomes **turbulent**
- If the swirling is regular and repeatable, it is termed a **vortex** or an **eddy**
- **Transition**
- The region in the b.l. where the orderly laminar layers start to mix together, but before they really start swirling, is called the **transition region**.
- The transition region is usually is a fairly small region.



Flow Separation

- As a turbulent boundary really starts to swirl, the BL thickness starts to grow even faster - the flow is so mixed, it starts to flow back towards the front
- The outside, original fluid is moving over a large SEPARATION bubble created by the turbulence
- Inside the bubble, the flow is moving back up the surface. This is called **flow separation**.
- The front of the bubble, where the outside fluid turns sharply away from the surface, is called the **point of separation**; the back of the bubble, where the outside fluid turns back to follow the surface again, is called the **point of reattachment**.
- If the region of flow separation extends past the surface, this region is called a **wake**.



The Reynolds Number

$$Re = \frac{L \cdot V \cdot \rho}{\mu}$$

Where: L = characteristic length
 V = freestream velocity
 μ = kinematic viscosity
 ρ = air density

- Turbulent flow results when the Reynolds number exceeds a certain value: typically 3×10^5
- For a tennis ball L would be equal to the diameter of the ball; on a wing L would be a "chord" length (the length of a line drawn from the leading to trailing edge of the wing).

The Reynolds Number

- Re is used describe the set of conditions under which an object will undergo flow transition (when the BL transitions from laminar to turbulent)
- This is called the critical Reynolds number **Recrit**.
- Specific geometries or objects have a different Recrit.
- A turbulent boundary layer can actually stay attached to the object longer than a laminar boundary layer.
- That means **flow separation is delayed** and there is less drag. Less drag can mean the flight of the ball is longer and/or faster. This is exactly why there are dimples on golf balls. Originally, golf balls didn't have dimples, but people observed that used balls that were roughed up flew longer than new balls. Eventually they designed golf balls with dimples in them.

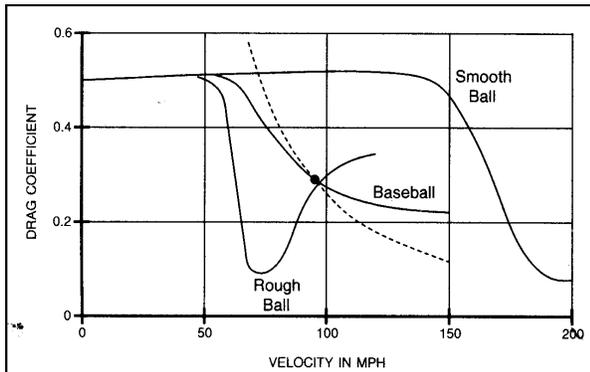
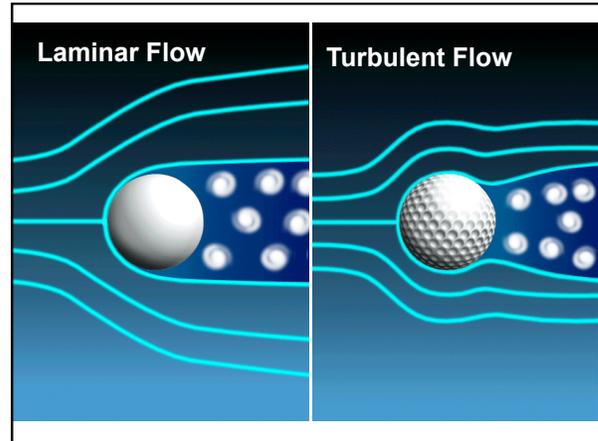
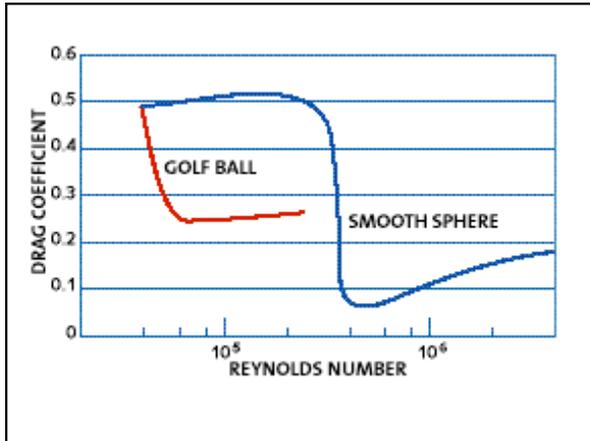


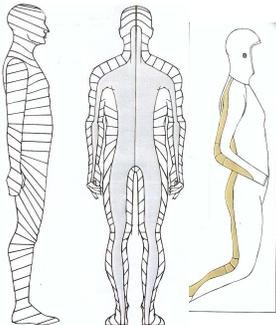
FIGURE 2.1 The drag coefficient vs. ball velocity for various balls the size of a baseball. At the broken line the force on the ball equals gravity.

1. Stretch fabrics with appropriate surface roughness can induce flow transition on limb segments.
2. The major innovation of the SWIFT suit was the use of 5 different fabrics over various body segments: "ZONED AERODYNAMICS"



Suit Design

1. Seams – placed parallel to flow
2. Ventilated areas, major seams, graphics moved to back, out of airflow
3. Suit cut and seaming designed to minimize wrinkling at maximum limb velocities



Athlete Utilization at 2000 Sydney Olympics

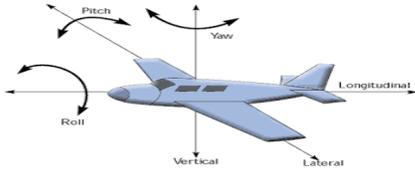
- 9 athletes wore the suit
- 6 advanced to the semi-final or final of their event

Medallists:

- Women's 100 m - gold (used in quarter final)
- Men's 400 m - silver (used in final)
- Men's 4x400 m relay - gold (used in final by 2 athletes)
- Women's 400 m - gold (used in final) - seasonal best performance

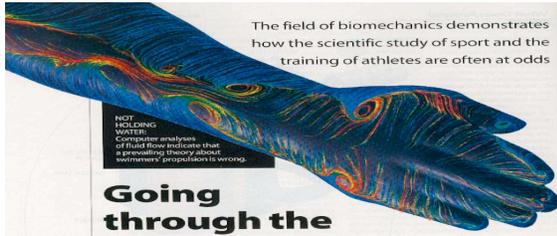
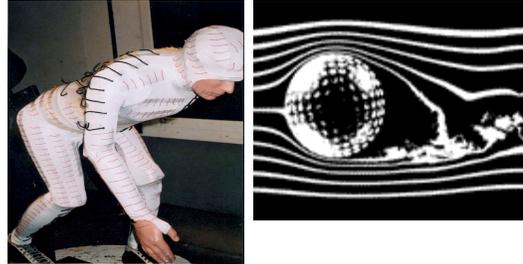


How can we measure drag?
U of Washington Kirsten Wind tunnel



Flow visualization techniques to make fluid flow visual

Smoke, helium bubbles, wool tufts, CFD

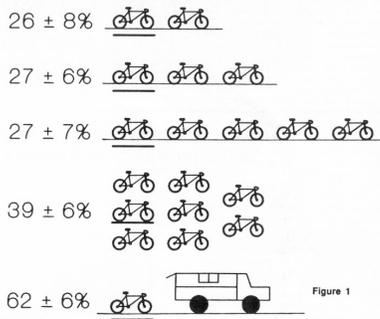


Drafting



Aside from drafting behind cars or motorcycles, riders can draft behind one another.

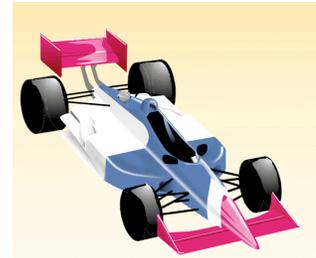
Energy Savings Drafting Formation



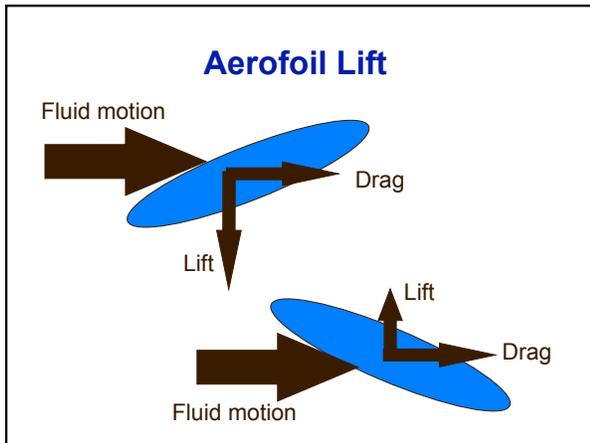
Reduction in VO₂ due to drafting behind different numbers of riders and a vehicle at 25 mph. The underlined rider represents the position of the test subject. All reductions are significant compared to riding alone at 25 mph.

Fluid Lift Force

Lift Forces are always directed perpendicular to the oncoming flow.



Lift forces are not necessarily directed upwards (e.g. aerofoil of a racing car).



Factors Causing Lift

$$F_L = 0.5 C_L A \rho v^2$$

Where: F_L is the lift force

- C_L is the coefficient of lift (an index of the object's "lift produce-ability")
- A is the area of the body on which pressure acts
- ρ is the density of air
- v is the relative velocity

Speed Skiing

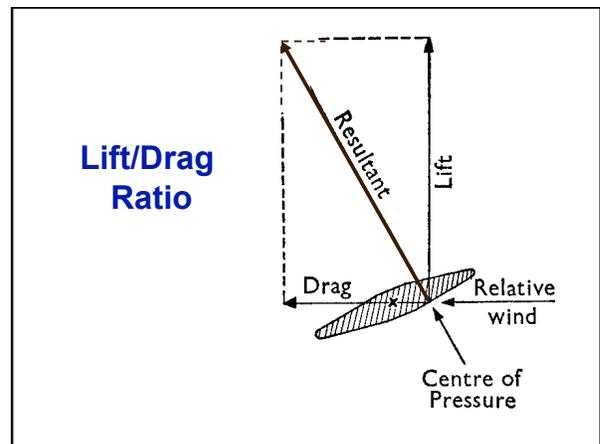
- involves developing maximum velocity through a measured (100 m) trap
- World Record: Phillippe May (Switzerland) 241 km/hr

- ### Speed Skiing Equipment
- Polyurethane coated suit - \$1,100
 - Special gloves with cuffs which keep airflow attached to suit
 - Weighted poles which are custom bent around body; special cups direct flow over hands - like nosecone on jet aircraft
 - "Darth Vader" helmet - must fit through 40 cm hoop - \$1,000
 - Leg fairings - up to 35 cm front to back
 - 240 cm long wooden/steel skis - weigh 25 lb
 - **How to go fast:**
 - stay in a tight "French" tuck for entire race
 - airflow through legs creates lower pressure area (higher velocity), which tends to push legs together.
 - If frontal area decreased by 5%, will cause 5.5 m/sec increase in velocity at 220 km/hour
 - If snow friction is decreased 5%, will cause 0.66 m/sec increase in velocity
 - Air density decreases with altitude:
 - Altitude Air density
 - 0 m 1.225 kg m-3
 - 650 m 1.15 kg m-3
 - 2000 m 1.0 kg m-3
 - Races at higher altitude have higher speed

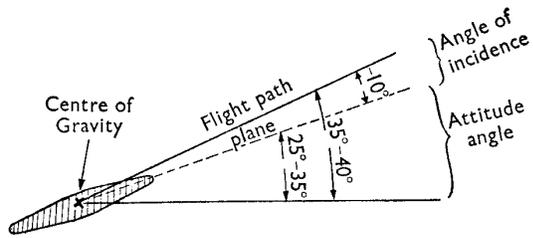
Speed Skiing

Other ways to increase downhill velocity:
 Increase skier mass (weighted vests; weighted poles)
 increase lift/drag ratio - (less snow friction force) - up to a point between 3 and 7 degrees; at larger torso angles, you lose stability - if skis lose contact with snow, you are out of control!

Torso Angle	Lift/ Drag ratio
0 degrees	0.139
3	0.25
7	0.417
10	0.55

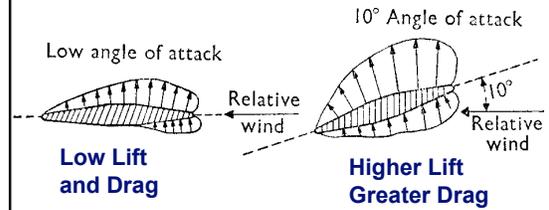


Angles During Flight



Angle of Incidence (Attack) = Attitude angle – Angle of Flight (relative wind direction)

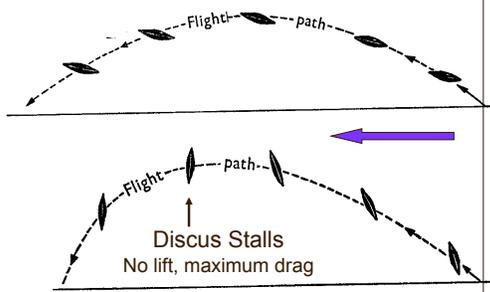
Angle of Attack



Angle of Attack =

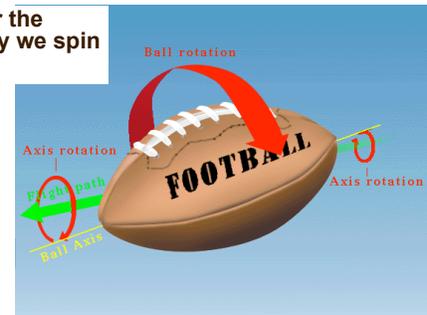
Attitude angle – Angle of relative wind

Flight Path of a Discus



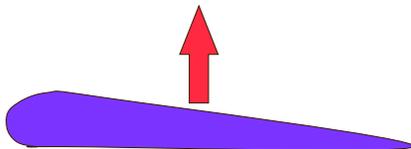
Football Angle of Attack

Remember the reason why we spin a football?

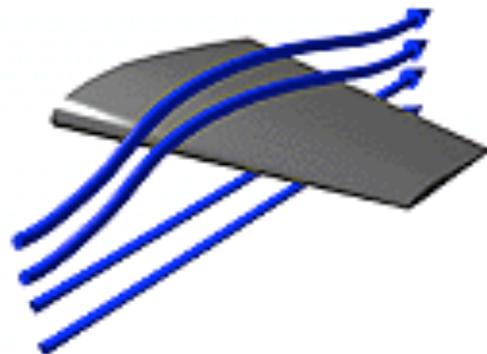


Bernoulli's Principle

Pressure $1/\alpha$ velocity



Air has to travel further over the top of the airfoil, hence greater velocity and less pressure.



Magnus Effect (already covered)

The Magnus force is not the same as the Bernoulli principle.

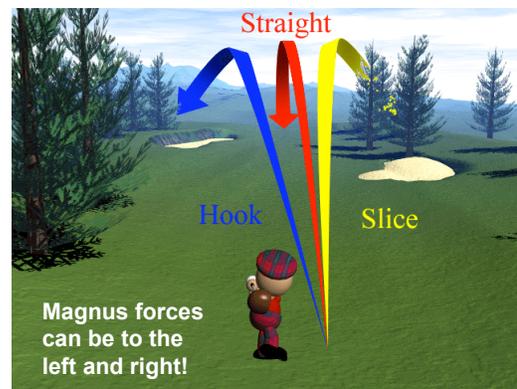
See discussion regarding tennis coaching to review the Magnus force effects.



Magnus Force

- The Magnus force is due to the imbalance of resistive forces on the ball that follows from the imbalance of velocity of the air flow spinning past the ball, is proportional to spin frequency, air velocity and the value of the drag coefficient at the ball velocity.
- "...is not quite the same as the Bernoulli effect; it is more than the Bernoulli effect, which is why it is called the Magnus effect and not the Bernoulli effect." R.K. Adair, The Physics of Baseball, 2nd edition, HarperPerennial, 1994.

Smoke Flow past a Golf Ball with Backspin



Bigger Golf ball

- Question: Top flight Magnum are a slightly larger golf ball. The company maintains that they "fly straighter". That is to say, it is harder for the duffer (e.g. me) to slice and/or hook them.
- Why?



Questions

- Can you explain from a mechanical perspective the following?
 - Viscosity
 - Boundary layer separation
 - Magnus forces
 - Airplane Wing Lift
 - Benefit of Drafting
 - Golf Ball Dimples