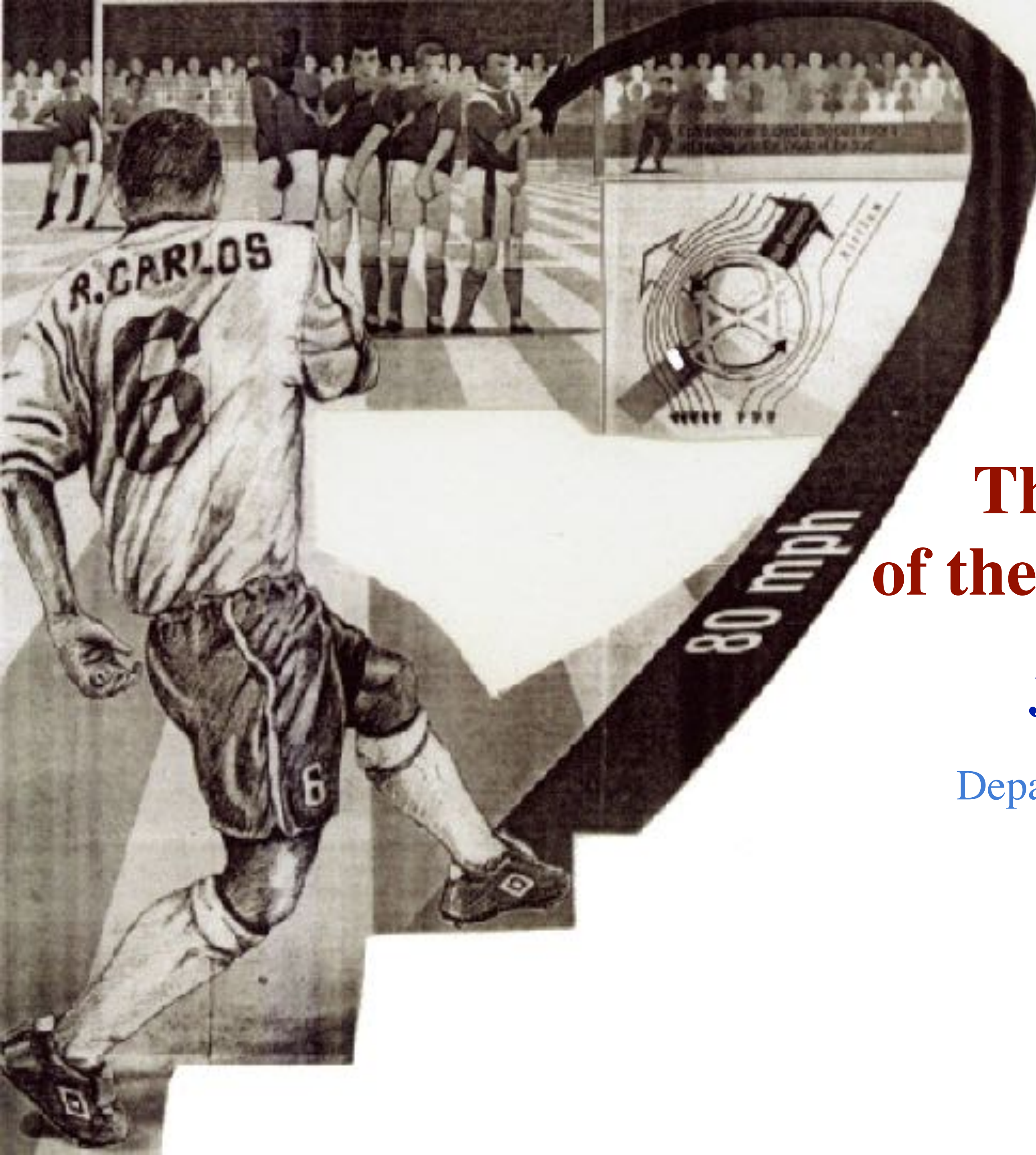


The aerodynamics of the Beautiful Game

John W. M. Bush

Department of Mathematics
MIT

Human inquiry

The question → The answer

Scientific inquiry

Skeptical assessment of the answer

Scientific research

Deduce a new, improved answer

My first scientific question...

Why do soccer shots occasionally bend, wobble?

Frank Lampard

Frank Lampard

Keisuke Honda

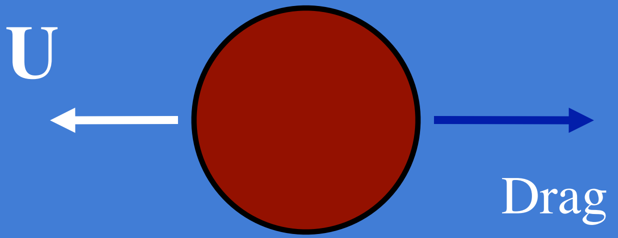
Keisuke Honda

OUTLINE

Translation of a sphere

- aerodynamic drag
- Reynolds number
- boundary layers
- boundary layer separation
- surface roughening

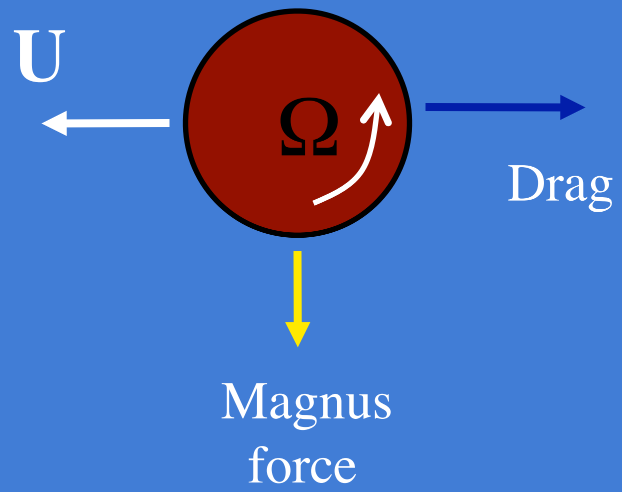
translating ball



Translation of a spinning sphere

- the Magnus effect
- the reverse Magnus effect

translating,
spinning ball



Striking the ball

- the dynamics of impact

Applications

- soccer
- tennis
- golf
- baseball
- cricket

References

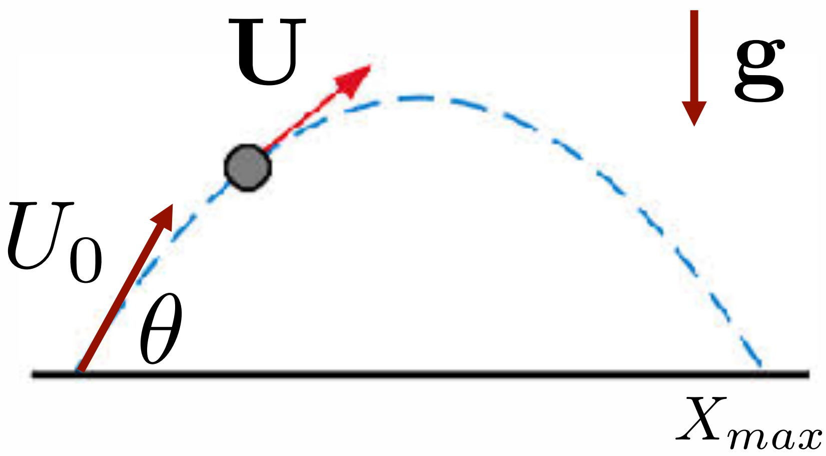
- Daish, C.B., 1972. The Physics of ball games
- Shapiro, A.H., 1956. Shape and flow
- Mehta, R.D., 1985. Aerodynamics of sports balls, *Ann. Rev. Fluid Mech.*
- Bush, J.W.M., 2013. The aerodynamics of the beautiful game, in *Sports Physics*, Ed. C. Clanet, Polytechnique Press, Paris.
- Clanet, C. 2015. Sports Ballistics, Ann. Rev, Fluid. Mech.

A preliminary question...

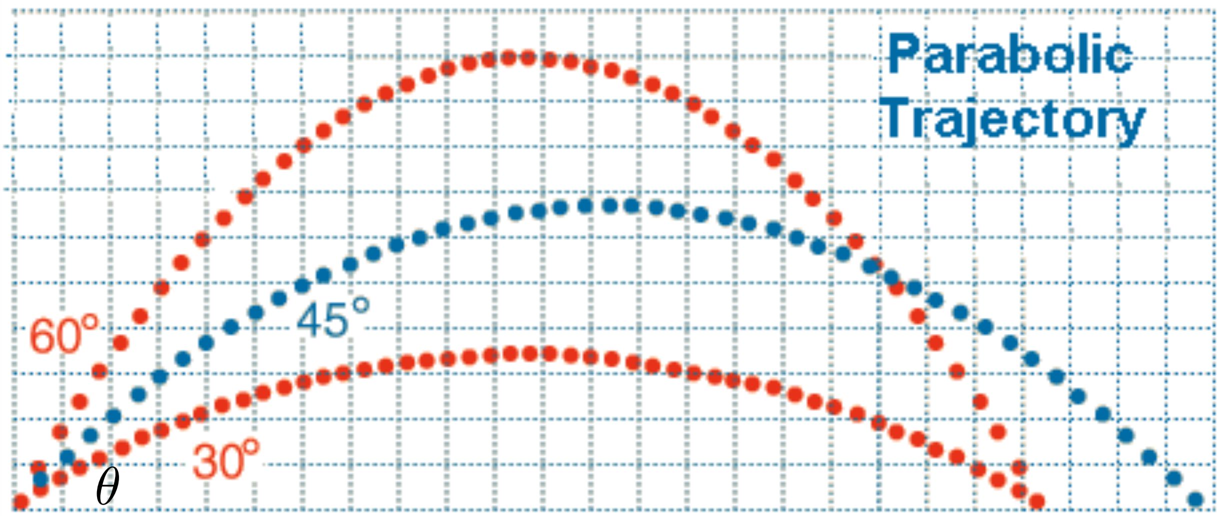
What trajectory does one expect a soccer ball to follow?

Trajectory equation in vacuo

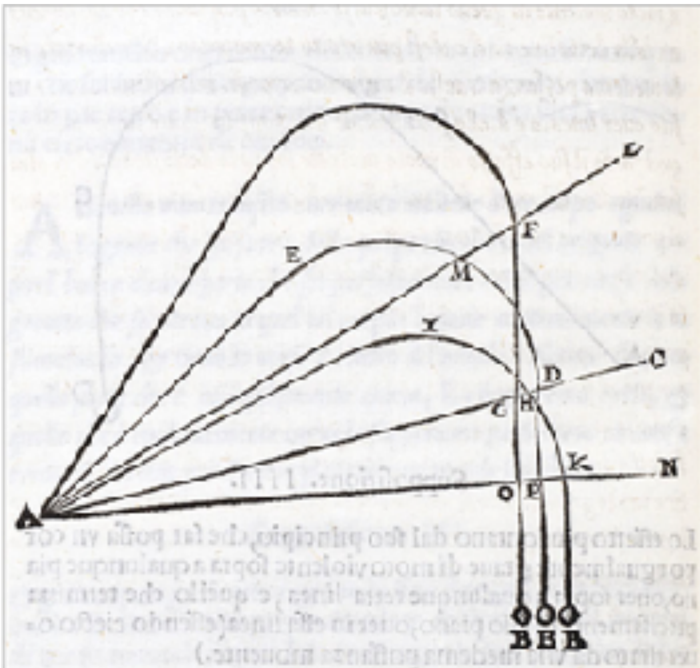
$$m\frac{d\mathbf{U}}{dt} = m\mathbf{g}$$



Range: $X_{max} \sim \frac{U_0^2}{g} \sin\theta\cos\theta$



Ballistics



Niccolo Fontana Tartaglia
(1499-1557)

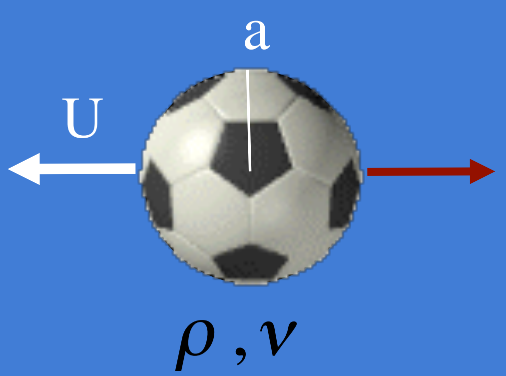
- **cannon balls in flight do not follow parabolic trajectories**

Shouldn't the trajectory just be parabolic? No. Why not?

Aerodynamic drag

$$\boxed{D \sim \rho \quad U^2 \quad a^2}$$

Drag density speed radius



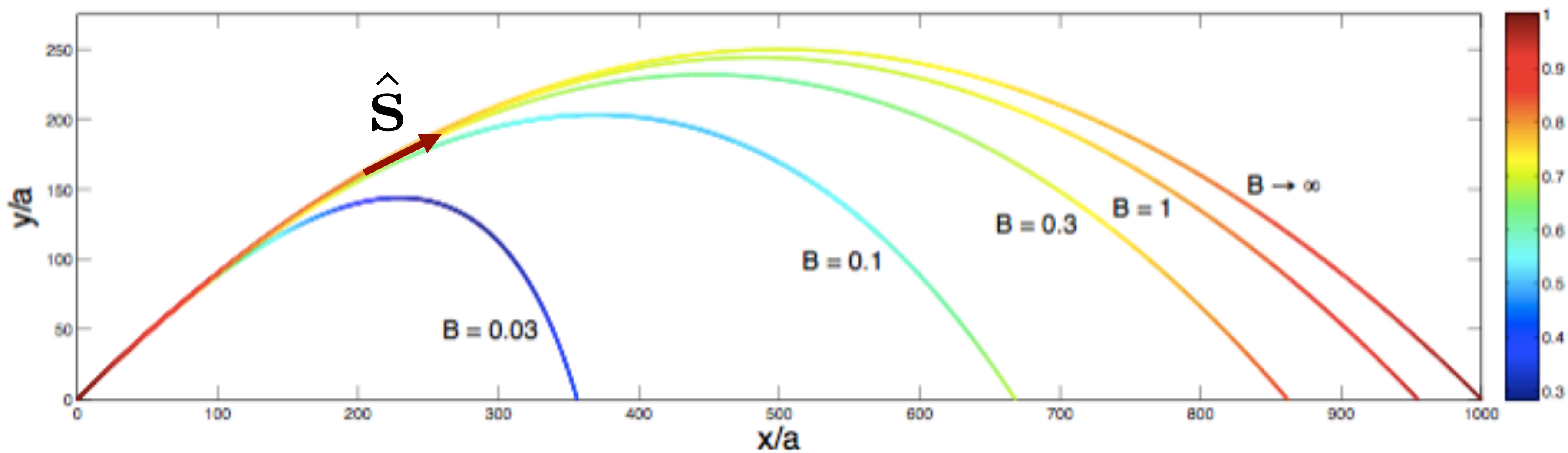
- the force you feel in extending your hand out the window of your car

But when is it important?

Trajectory equation in air: no spin

$$m\frac{d\mathbf{U}}{dt} = m\mathbf{g} - C_d\,\pi a^2 \rho\, U^2\,\hat{\mathbf{s}}$$

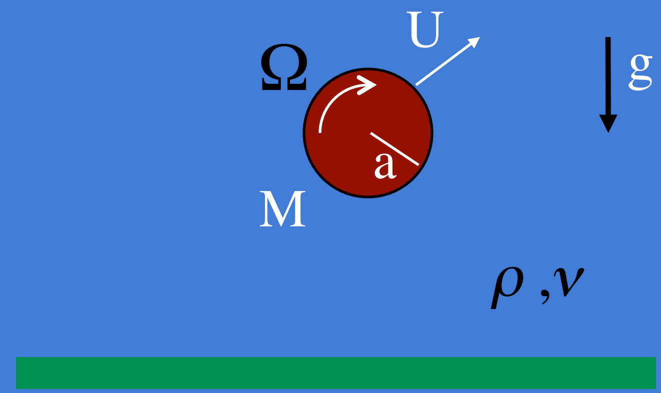
AIR DRAG



$$B = \frac{weight}{air\ \ drag} = \frac{mg}{\pi a^2 \rho U_0^2}$$

Equation of motion of a ball in flight

$$\boxed{M\frac{d\mathbf{U}}{dt} = M\,\mathbf{g} + \mathbf{F}_{\mathbf{aero}}(\mathrm{Re},\mathrm{Ro})}$$



where $\quad \mathrm{Re} = \dfrac{Ua}{\nu} \quad , \quad Ro = \dfrac{U}{\Omega a}$

Ballistic Performance

$$\frac{\text{Weight}}{\text{Aero. forces}} = \frac{Mg}{\rho U^2 a^2 F(\mathrm{Re},Ro)} \sim \frac{M}{4a^2}$$

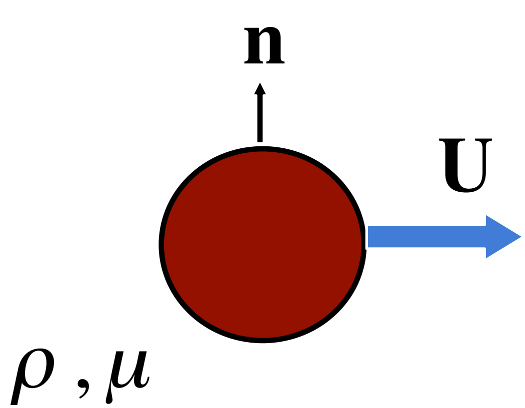
- indicates importance of aerodynamic forces on the ball's trajectory
- aerodynamic forces dominate for large, light balls

Sport	BP ($kg\,m^{-2}$)
Lacrosse	35
Cricket	32
Baseball	26
Golf	25
Soccer	15
Ping-pong	1.8

Translation of a sphere

Navier-Stokes equations:

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u}\right) = -\nabla p + \rho\mathbf{g} + \mu\nabla^2\mathbf{u} \quad , \qquad \nabla\cdot\mathbf{u} = 0$$



Boundary Conditions

No-slip: $\mathbf{u} = \mathbf{U}$

Stress tensor:

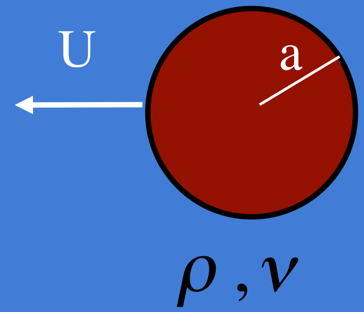
$$\mathbf{T} = -p\mathbf{I} + \mu\left(\nabla\mathbf{u} + (\nabla\mathbf{u})^T\right)$$

Hydrodynamic force on body:

$$\boxed{\mathbf{F_h} = \int_{\mathbf{S}} \mathbf{n}\cdot\mathbf{T}\ d\mathbf{A}}$$

Aerodynamic Drag: force resisting motion

$$D = \underbrace{\text{Pressure drag}}_{\rho\, U^2 a^2} + \underbrace{\text{Viscous drag}}_{\rho\, \nu \frac{U}{a}\, a^2}$$



Reynolds number:

$$\frac{\text{Pressure drag}}{\text{Viscous drag}} = \frac{Ua}{\nu} \equiv \text{Re}$$

Re << 1: viscous drag dominant

$$D = 6\pi\, \rho\, \nu\, U\, a$$

Re >> 1: pressure drag dominant

$$D = \tfrac{1}{2}\, \rho\, U^2 a^2$$

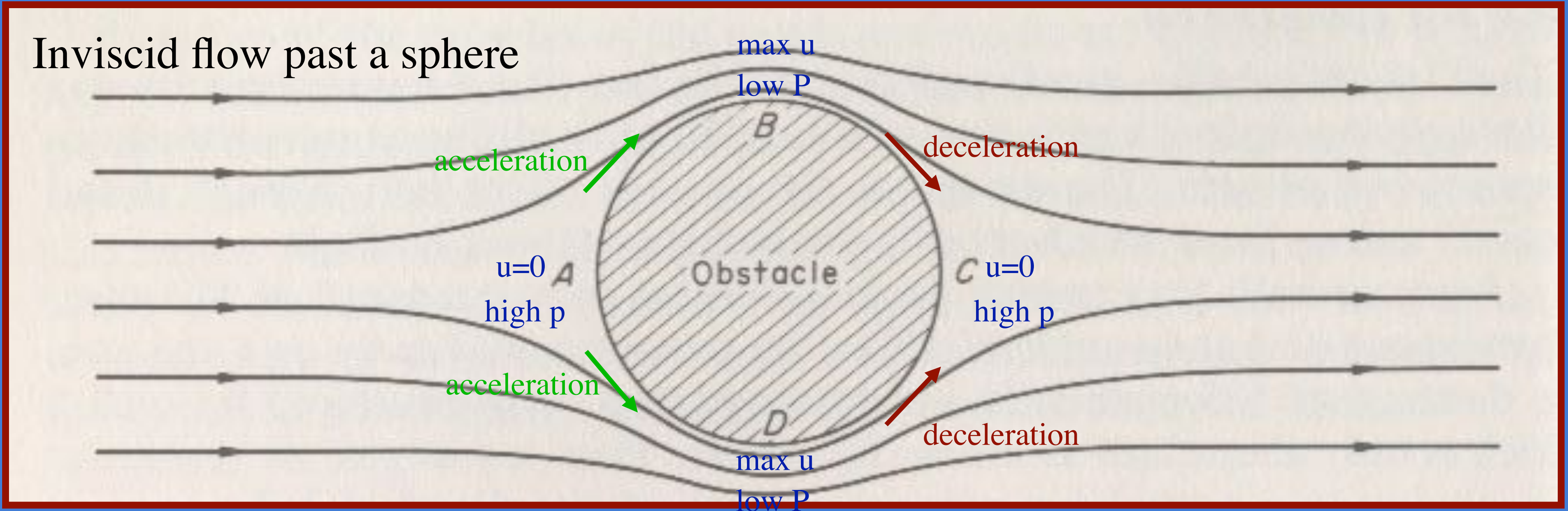
Sport	Re
Soccer	425,000
Cricket	150,000
Baseball	150,000
Tennis	122,000
Golf	79,000
Ping-pong	73,000

Momentum equation: $$\rho\left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u}\right) = -\nabla p + \rho\nu\,\nabla^2\mathbf{u}$$

INERTIA VISCOUS

Steady inviscid flow: $$\nabla\left(P + \tfrac{1}{2}\rho U^2\right) = 0$$

Bernoulli's equation: $P + \frac{1}{2}\rho U^2 =$ constant throughout fluid

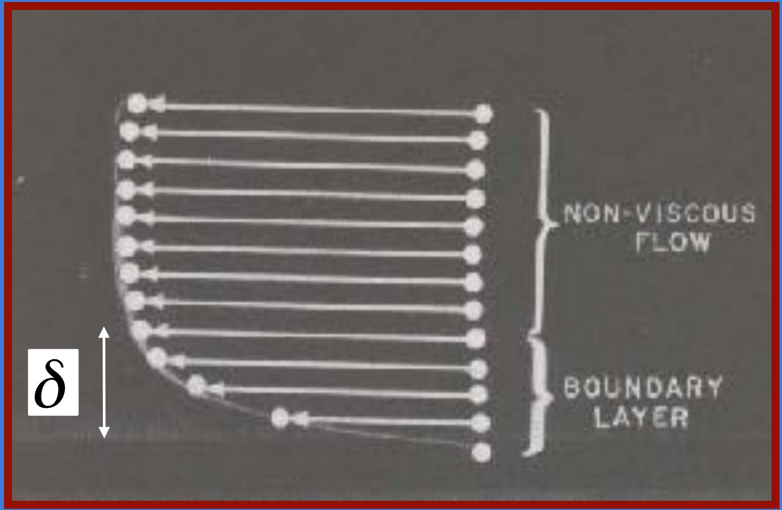


D'Alembert's Paradox: there is no net force resisting the motion of an obstacle translating steadily through an inviscid fluid

→ we can't bin viscosity

Boundary layers

- required by no-slip condition on body
- the thin layer adjoining the body surface wherein viscous effects dominate the flow



Boundary layer thickness δ

- prescribed by inertial-viscous balance:

$$\mathbf{u}\cdot\nabla\mathbf{u} \sim \nu\nabla^2\mathbf{u}$$

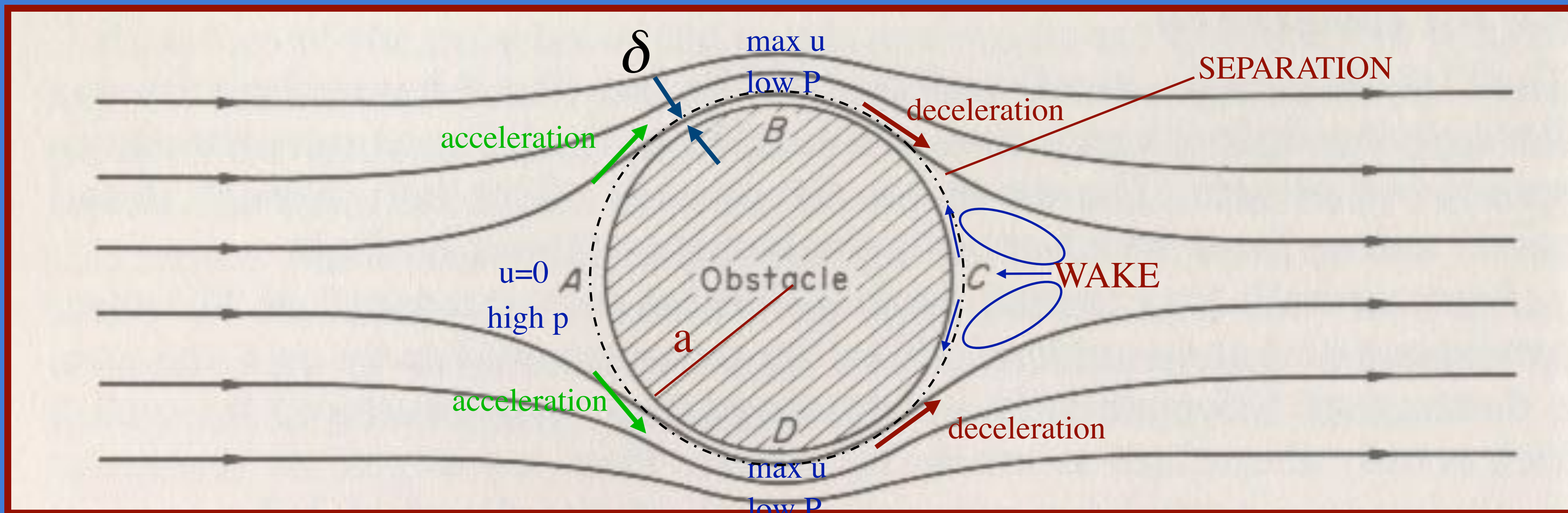
$$\rightarrow \quad \frac{U^2}{a} \sim \nu\frac{U}{\delta^2} \quad \rightarrow \quad \boxed{\delta \sim \frac{a}{\mathrm{Re}^{1/2}}} \quad \text{where} \quad \mathrm{Re} = \frac{U\,a}{\nu}$$

- for sports balls, Re >>1, so boundary layers are thin relative to ball

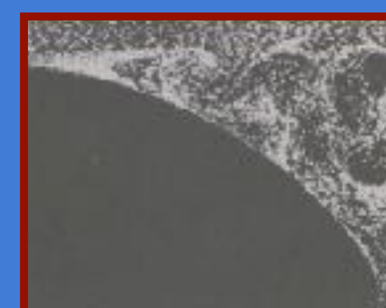
  e.g. baseball, soccer: $\delta \sim 0.1\,mm$

- boundary layers contribute a lateral stress (force/area): $\boxed{\tau \sim \mu\frac{U}{\delta}}$ SKIN FRICTION
- boundary layers also may alter details of flow around body, change pressure field

The influence of viscosity on high Re flow past a sphere

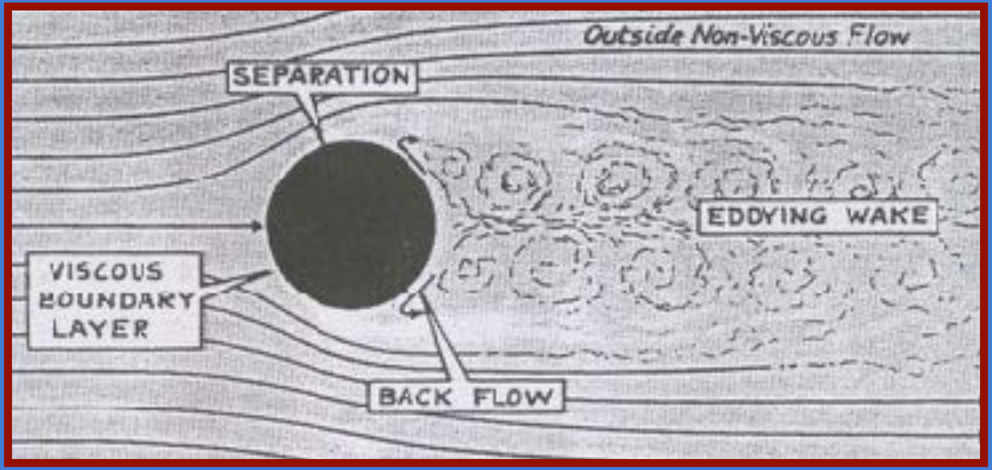


- viscous boundary layer of thickness $\delta \sim a\,\mathrm{Re}^{-1/2}$ adjoins sphere surface
- viscous resistance takes momentum out of boundary layer flow



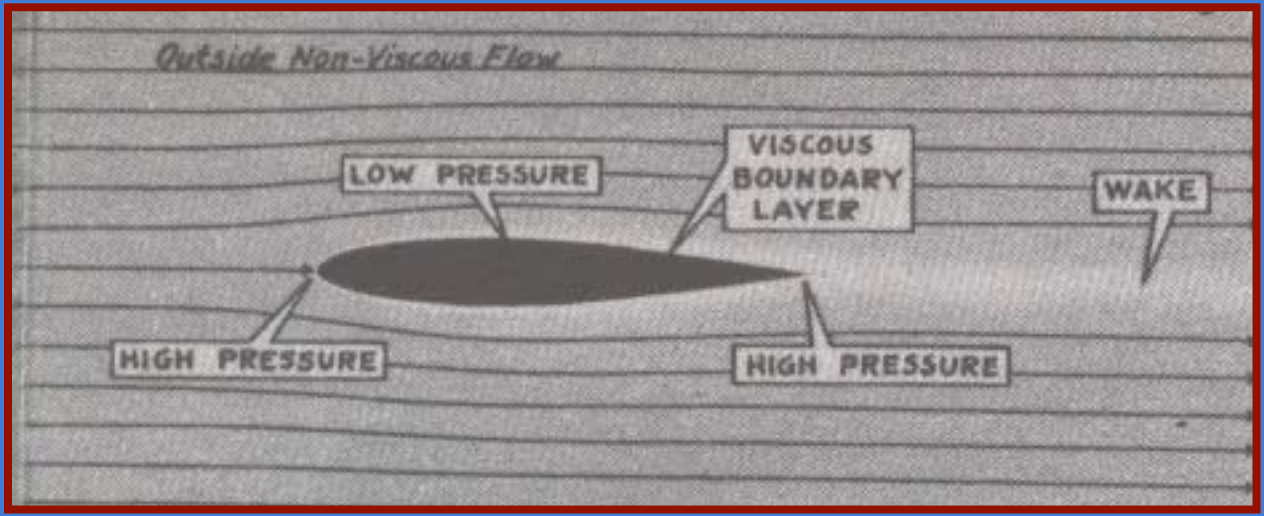
- boundary layer separation, stall: pressure within wake equals that at separation point
- symmetry in p field broken, low p wake → large pressure or `form' drag

Bluff body: drag due to pressure drop associated with b.l. separation



$$D_{bluff} \sim \Delta P\, a^2 \sim \rho\, U^2 a^2$$

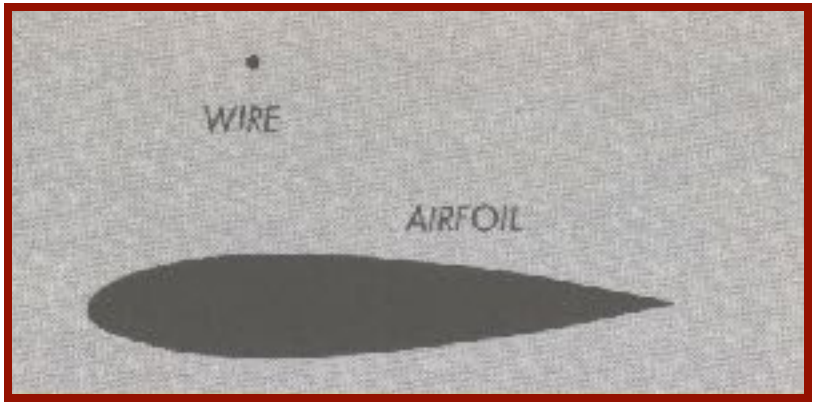
Streamlined body: drag due to skin friction

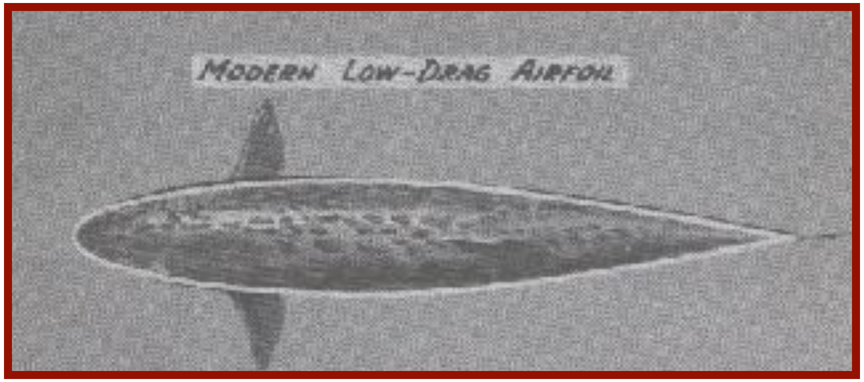


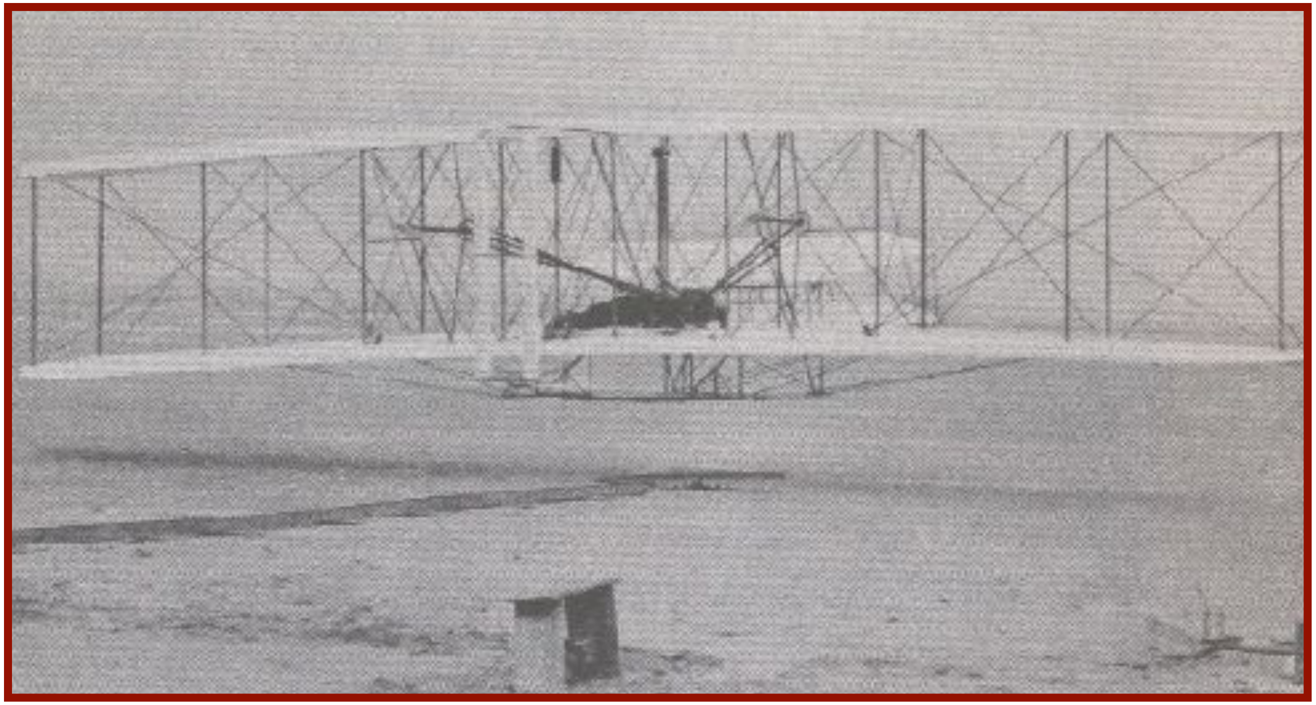
$$D_{stream} \sim \rho \nu \frac{U}{\delta} a^2$$

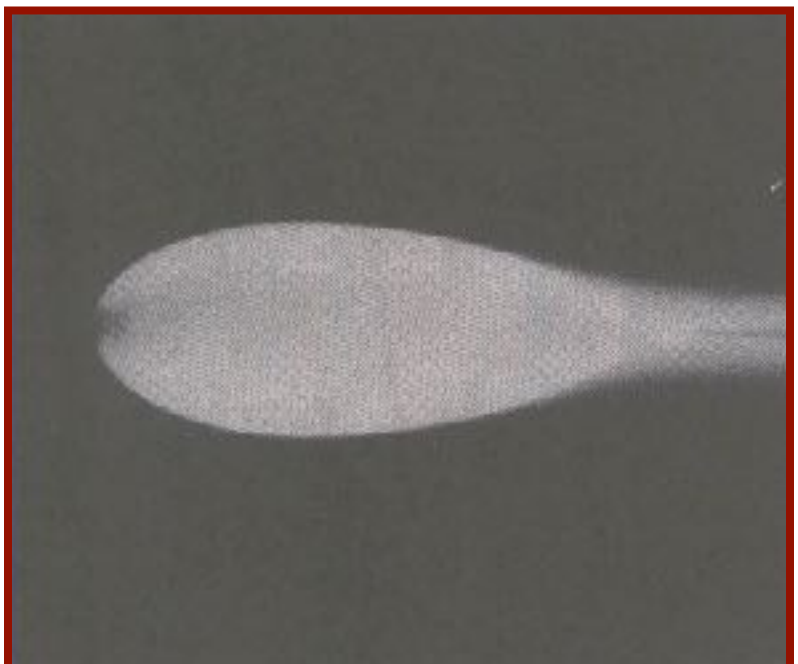
where $\delta \sim a\mathrm{Re}^{-1/2}$

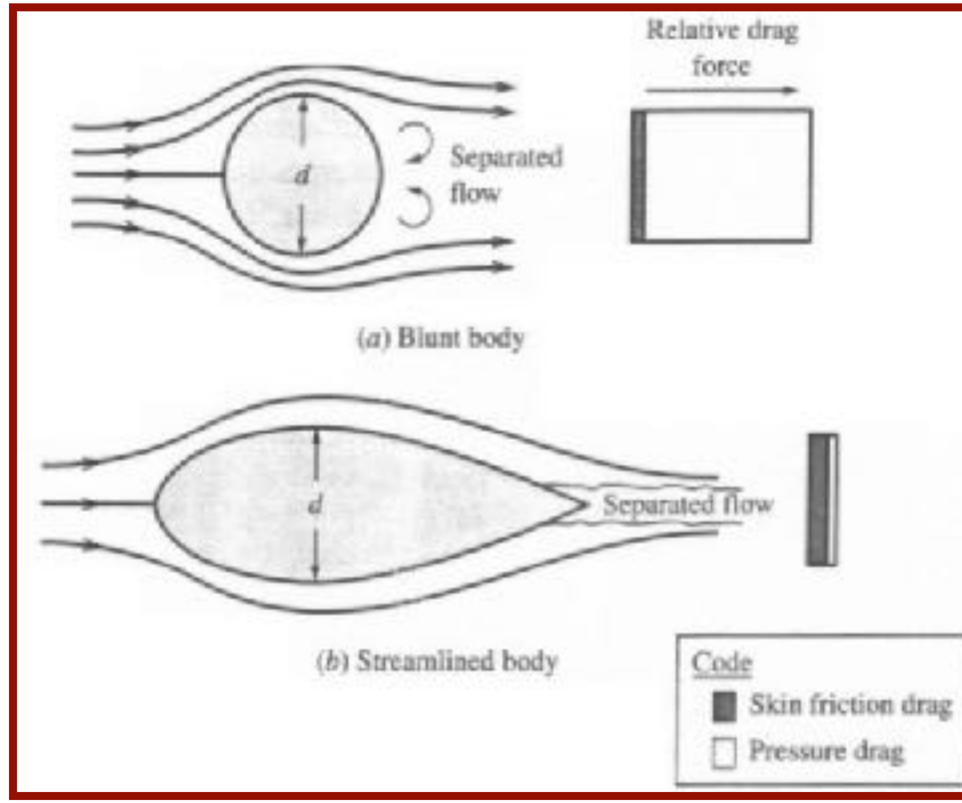
Ratio: $\dfrac{D_{stream}}{D_{bluff}} \sim \mathrm{Re}^{-1/2} << 1$ $\longrightarrow$ streamlining hugely important


WIRE
AIRFOIL

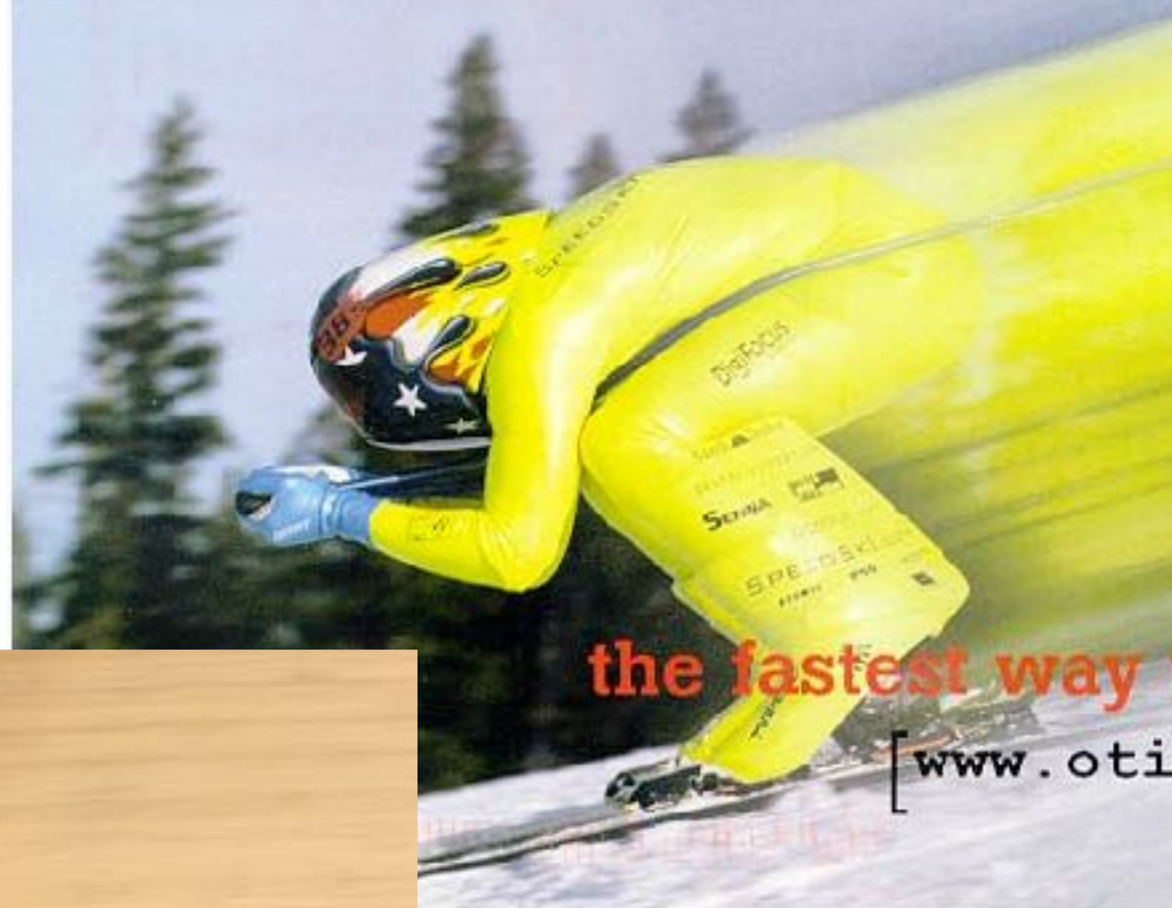

MODERN LOW-DRAG AIRFOIL

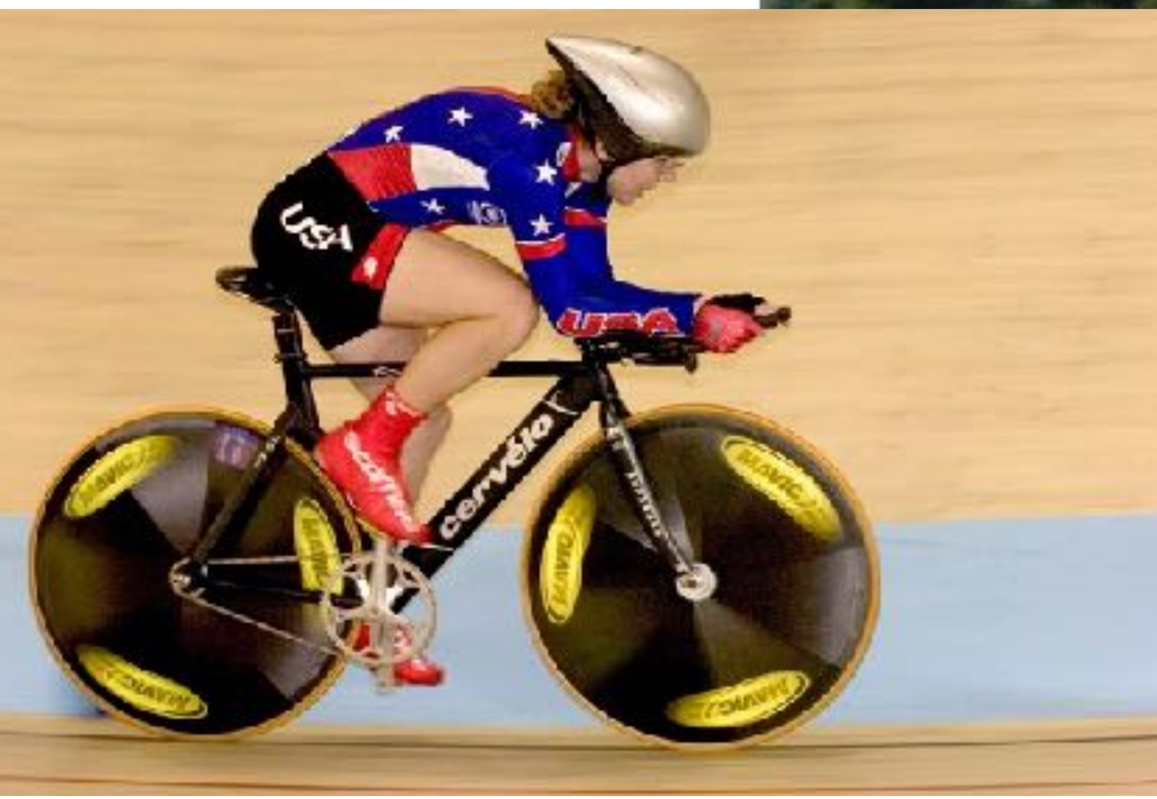




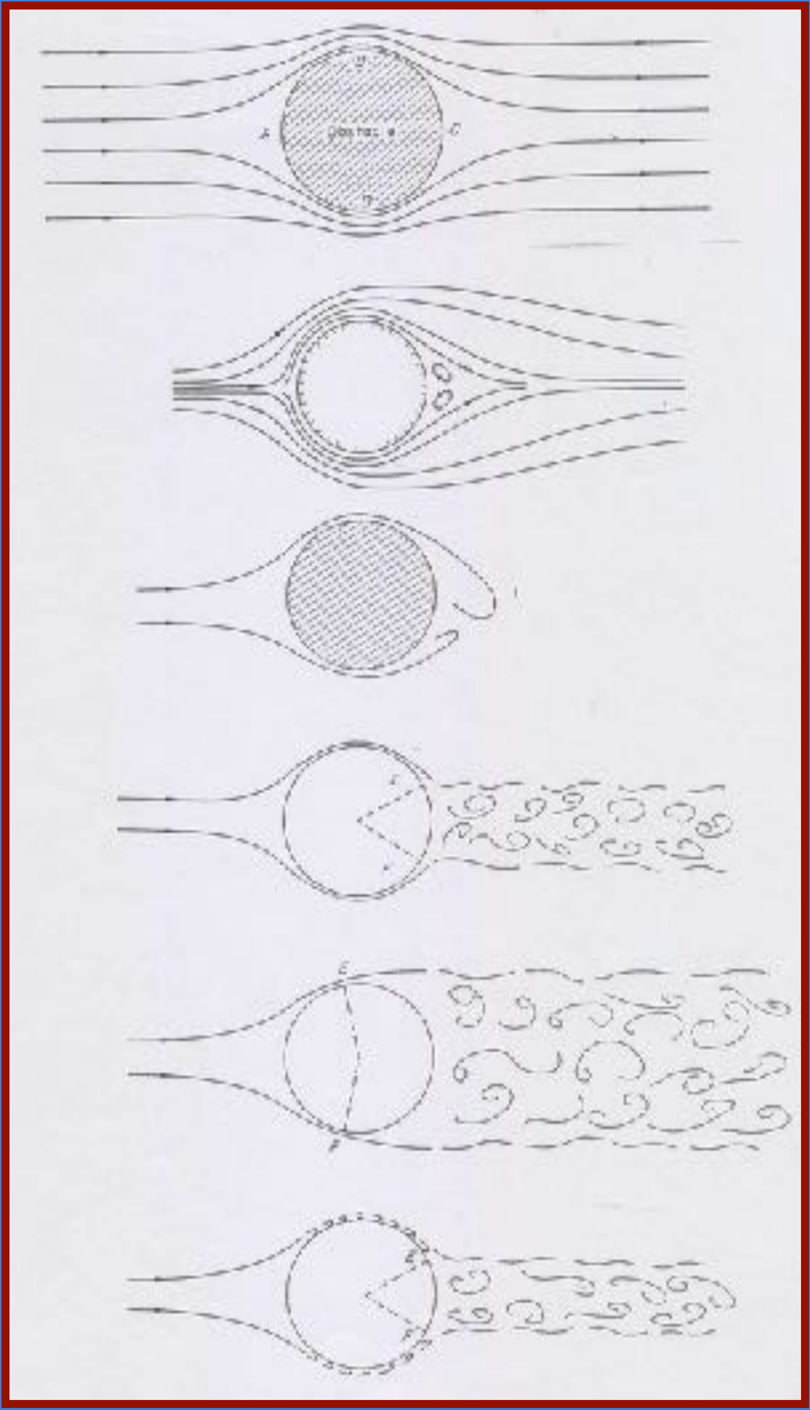

Relative drag force
d
Separated flow
(a) Blunt body
d
Separated flow
(b) Streamlined body
Code
Skin friction drag
Pressure drag

Streamlining in sport





Flow past a sphere: Re dependence



Re << 1: symmetric flow $\mathrm{Re} = \dfrac{Ua}{\nu}$

Re = 10: steady flow, boundary layer separation, attached eddies

30 < Re< 150: periodic vortex shedding

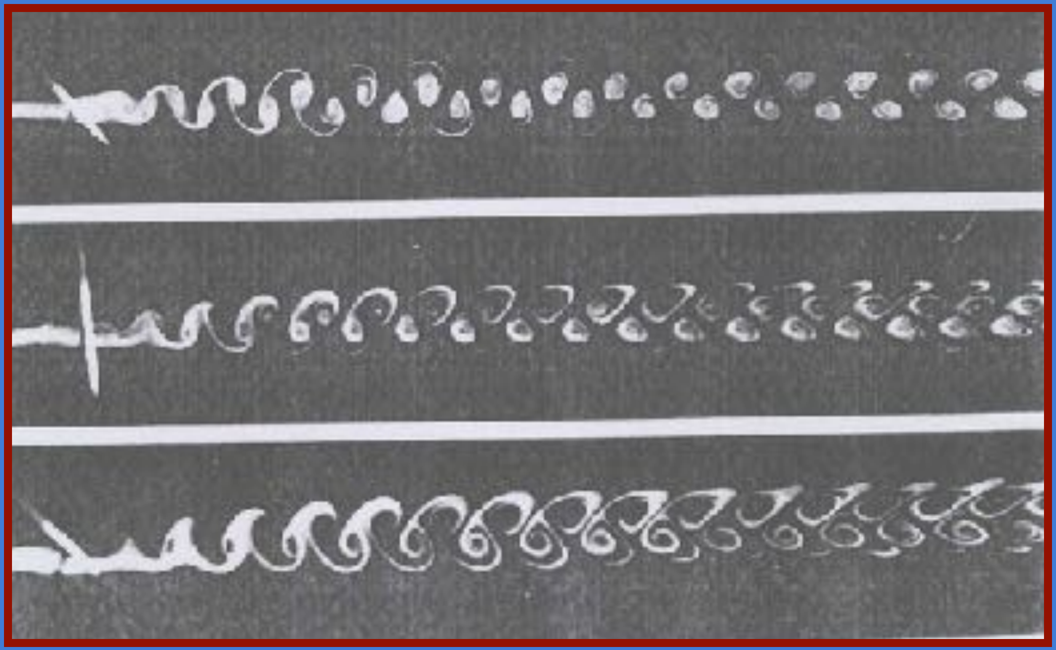
Re > 300: turbulent wake

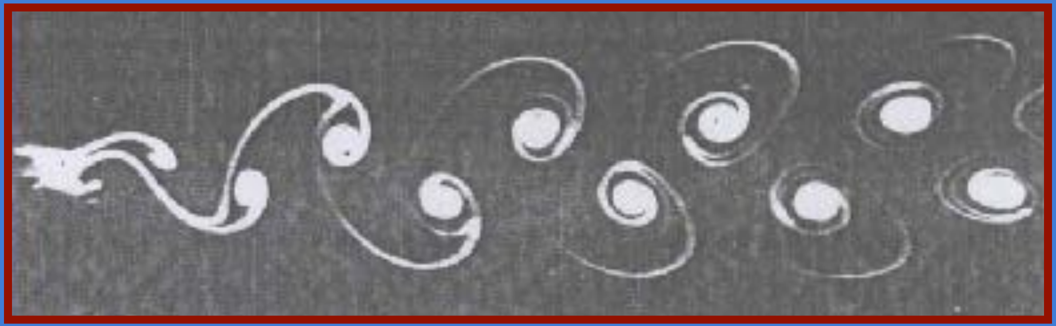
Re > 2000: fully turbulent wake

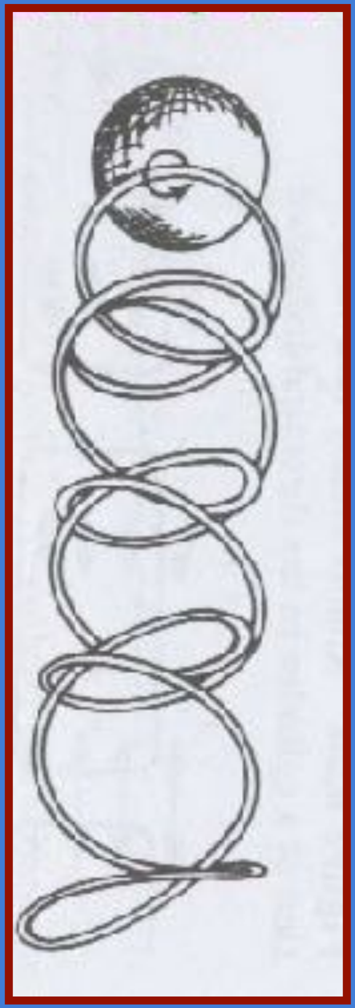
SPORTS BALL REGIME

Re > 50,000: turbulent boundary layer

Periodic vortex shedding in the wake of a cylinder

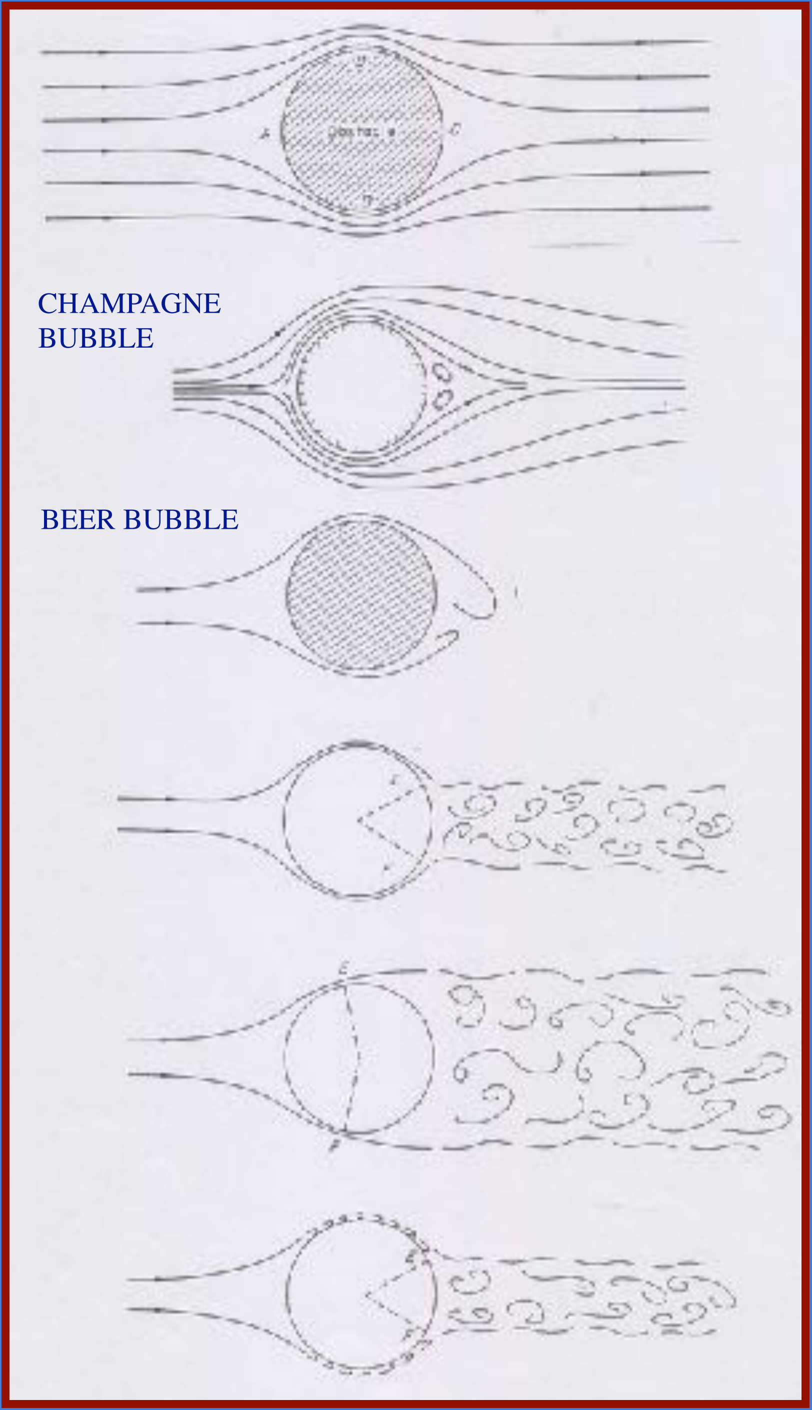






- analogous vortex shedding behind a sphere results in spiraling fireworks, bubbles in beer

Flow past a sphere: Re dependence



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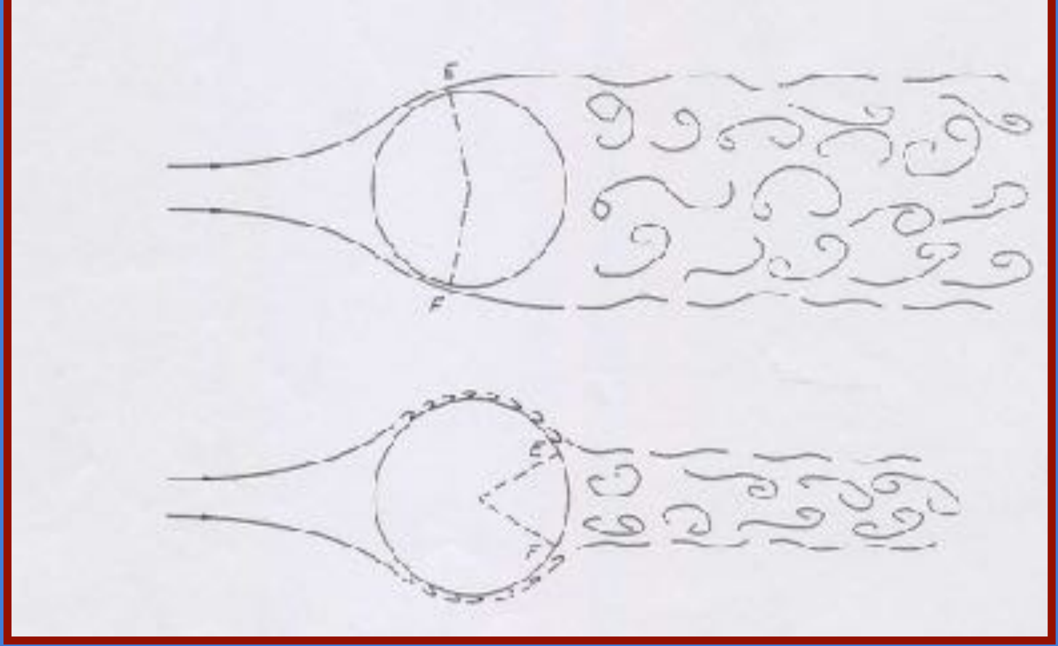
SPORTS BALL REGIME

Re > 50,000: turbulent boundary layer

Re > 2000: fully turbulent wake



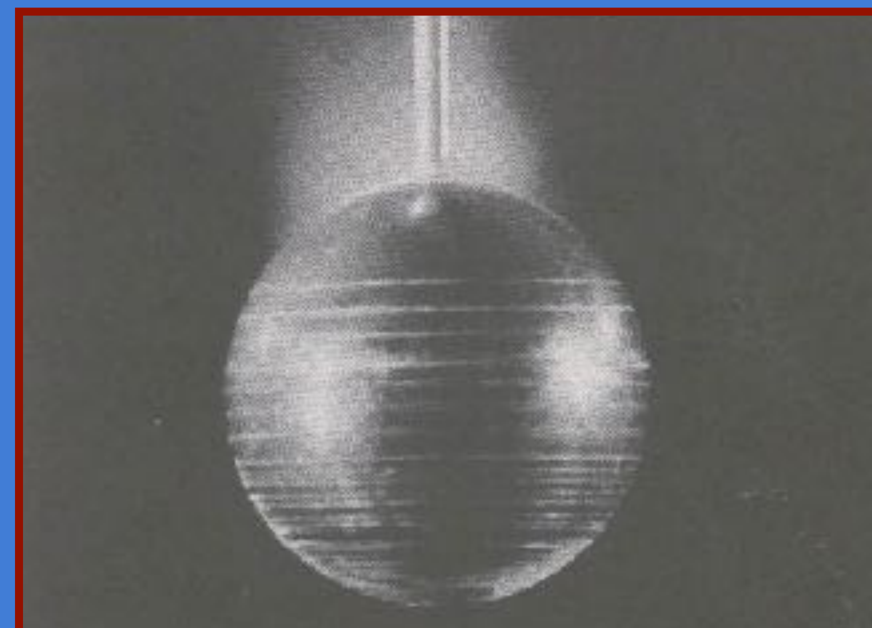
Re > 50,000: turbulent boundary layer

Drag Crisis

- the dramatic decrease in drag prompted by the onset of turbulence in the b.l.
- turbulence transfers momentum from stream into b.l., so delays b.l. separation
- the resulting reduction in the pressure drop and wake size decreases the drag
- this may be prompted at lower Re by surface roughness or stitches

Drag Crisis: can be promoted by surface roughening

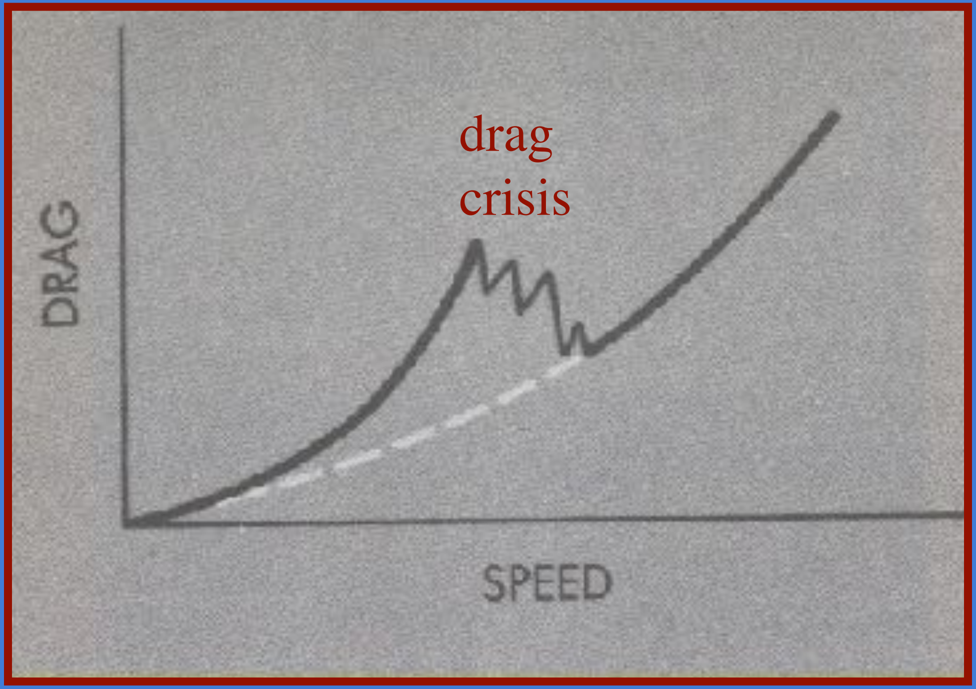
- hence stitching on baseballs and cricket balls, dimples on golf balls and fur on tennis balls

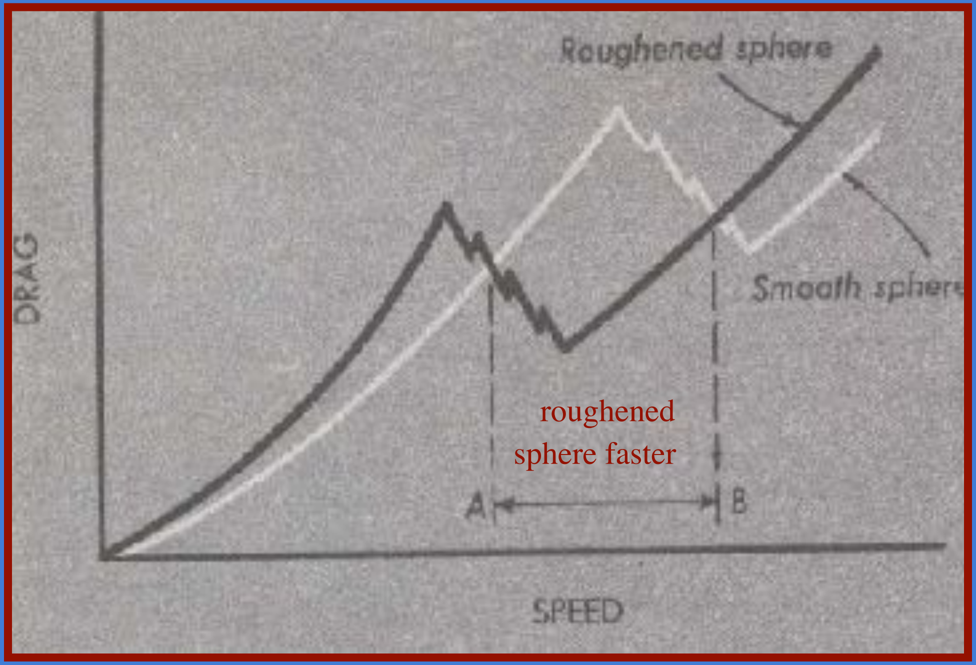


- laminar boundary layer
- broad wake
- large pressure drop

increase Re

- turbulent boundary layer
- narrow wake
- pressure drag greatly reduced


drag
crisis
DRAG
SPEED


Roughened sphere
Smooth sphere
DRAG
roughened
sphere faster
A
B
SPEED

DIMENSIONAL ANALYSIS

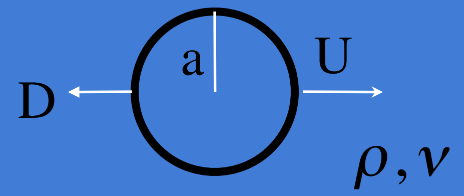
Fundamental Concept

The laws of Nature cannot depend on an arbitrarily chosen system of units.
A system is most succinctly described in terms of dimensionless variables.

Deduction of Dimensionless groups: **Buckingham's Theorem**

For a system with M physical variables (e.g. density, speed, length, viscosity) describable in terms of N fundamental units (e.g. mass, length, time, temperature), there are M - N dimensionless groups that govern the system.

E.g. Translation of a sphere



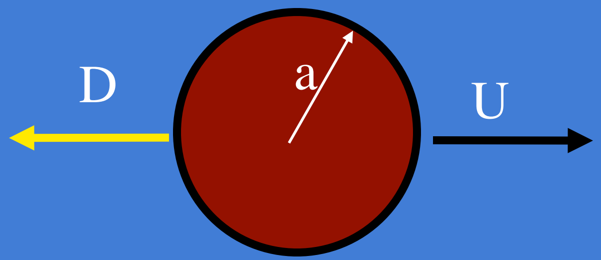
Physical variables: $U, \mathrm{a}, \nu, \rho, D \;\Rightarrow\;$ M = 5

Fundamental units: M , L , T $\;\Rightarrow\;$ N = 3

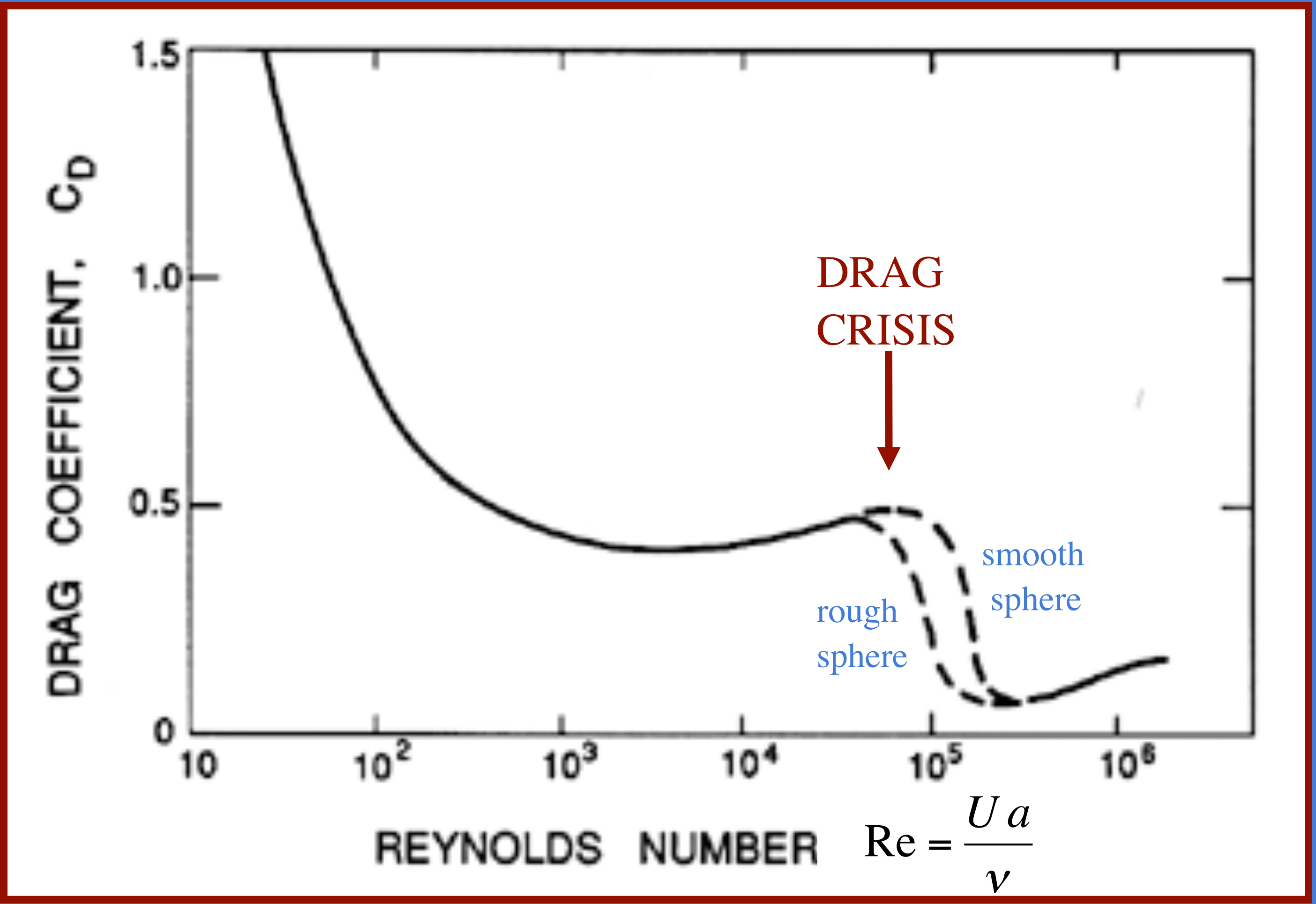
M - N = 2 dimensionless groups: $C_d = \dfrac{D}{\rho U^2}$, $\mathrm{Re} = \dfrac{U\mathrm{a}}{\nu}$

System uniquely determined by a single relation: $C_d = F(\mathrm{Re})$

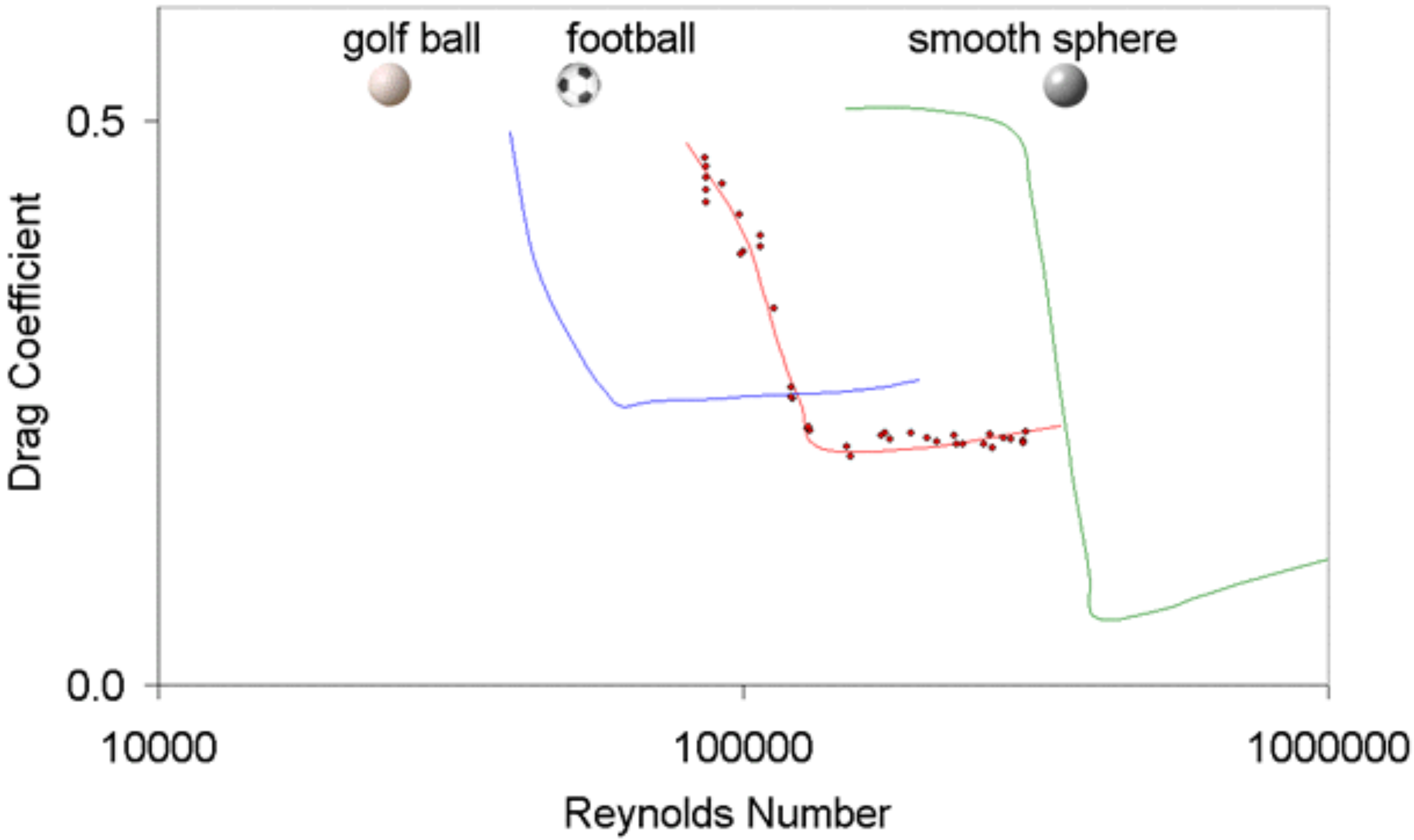
Drag: $D = C_D(\mathrm{Re})\,\rho\,U^2\,a^2$



Variation of C_D with $\mathrm{Re} = \dfrac{U\,a}{\nu}$:

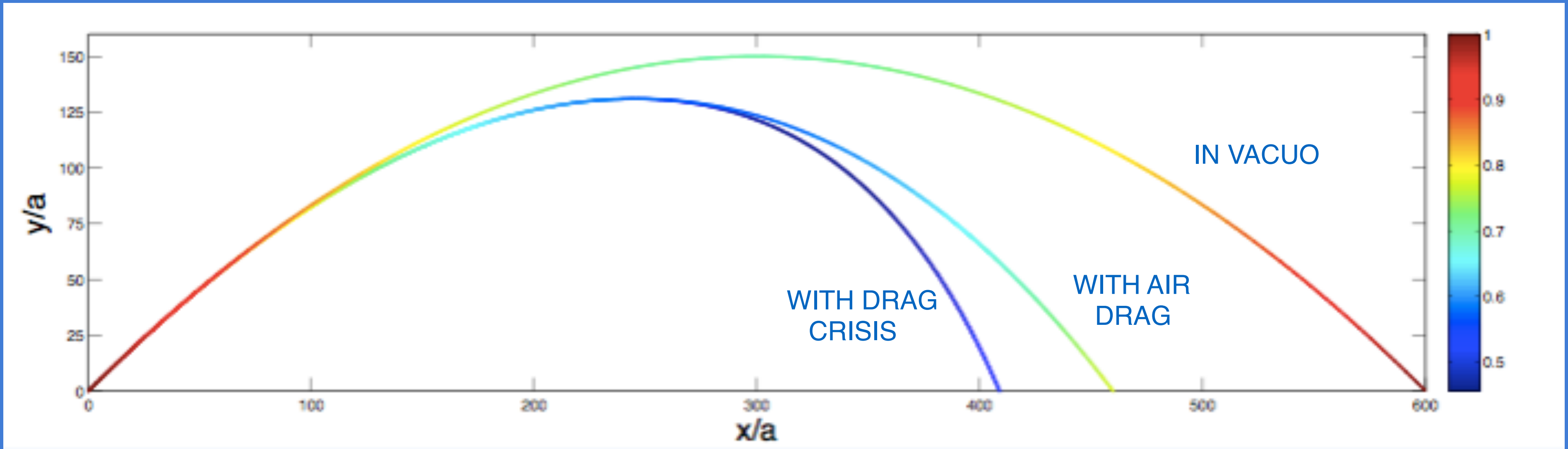


The effect of surface roughness on onset of drag crisis



- drag crisis prompted at lower Re by surface roughness

The effect of the drag crisis on the goal kick

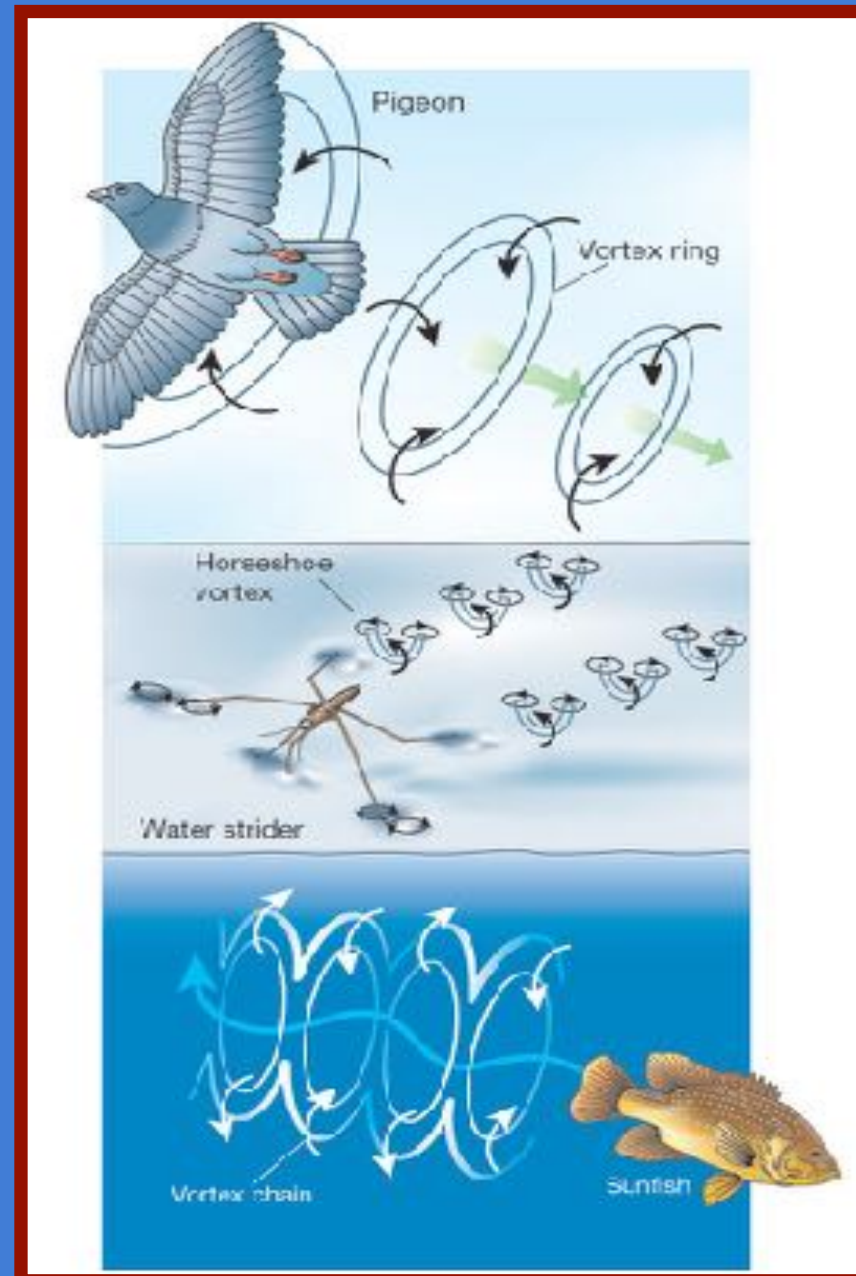


- the drag crisis is similarly important in shooting: shots often dip sharply as they approach the net, pass through the drag crisis threshold

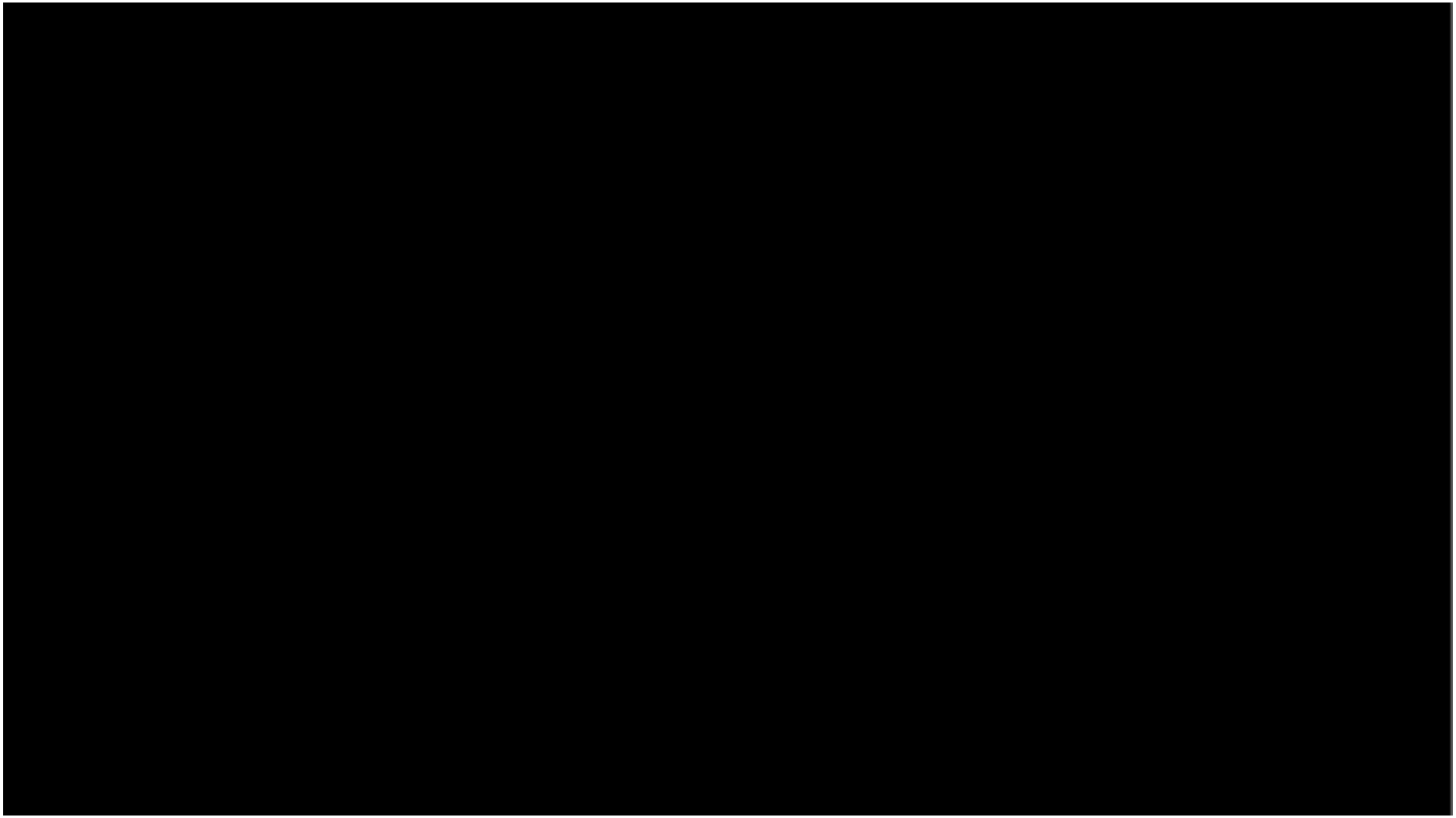
Propulsion

- stopping fluid creates drag, ejecting fluid creates thrust
- a rocket generates thrust by ejecting its fuel backwards

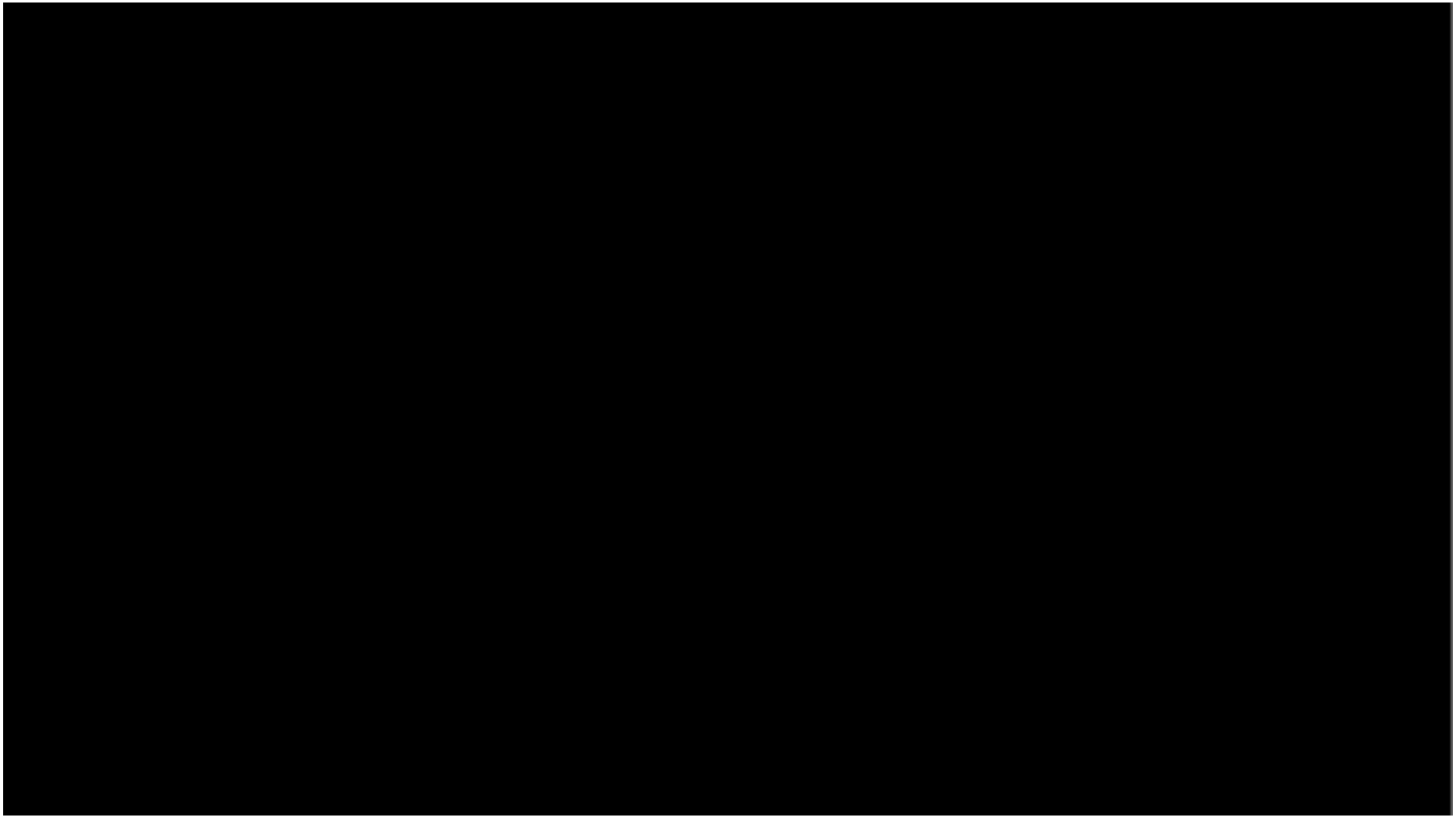
Propulsion by vortex shedding...



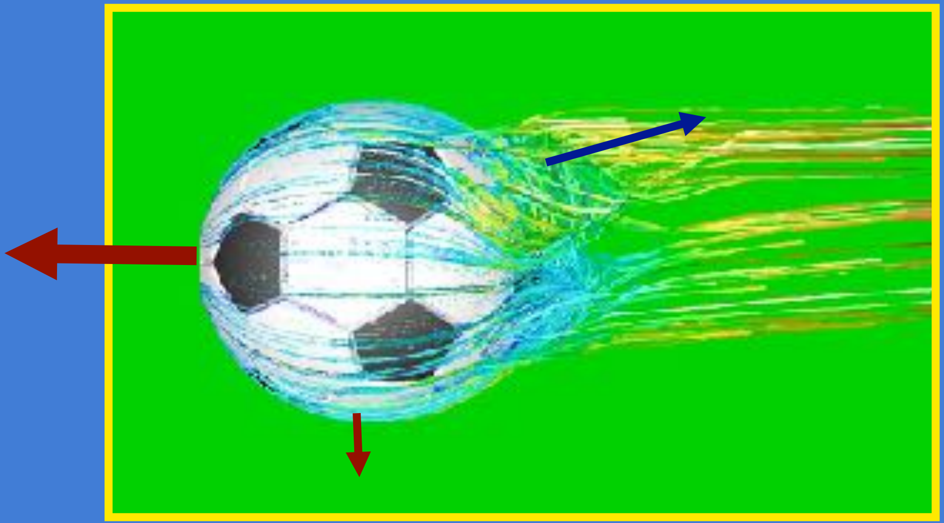
The flight of the humming bird

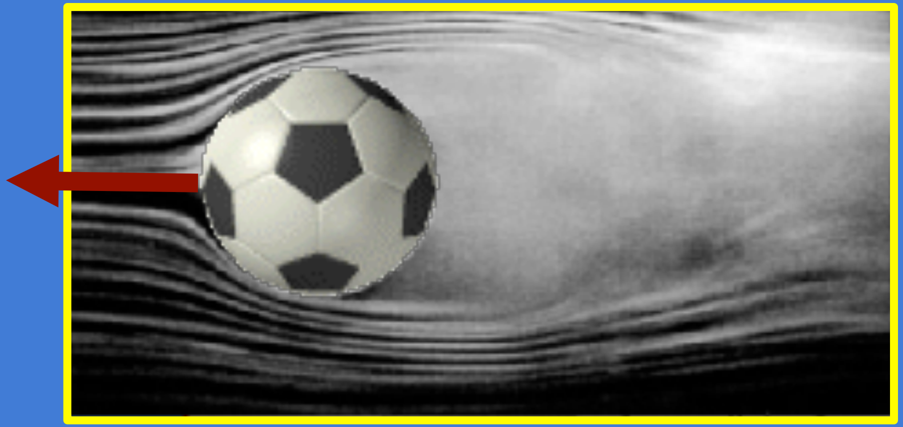


The flight of the humming bird



The flow around a soccer ball without spin

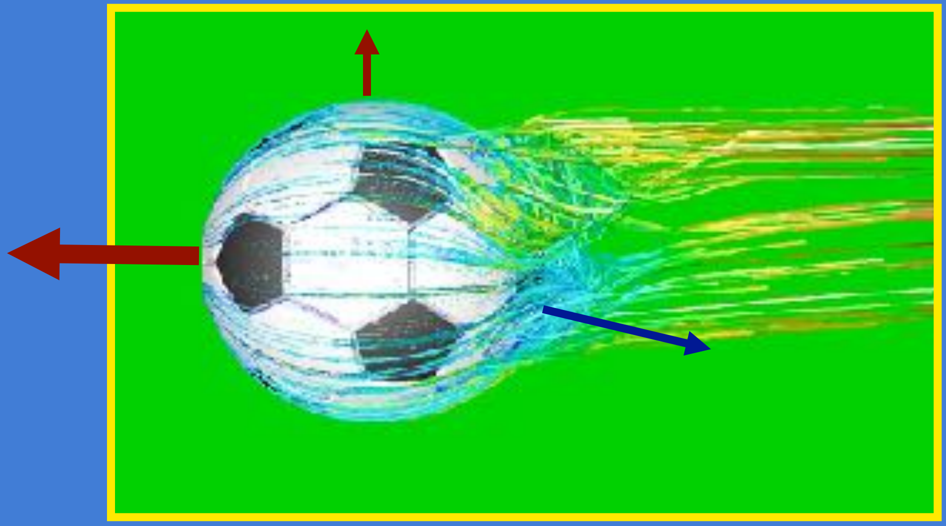


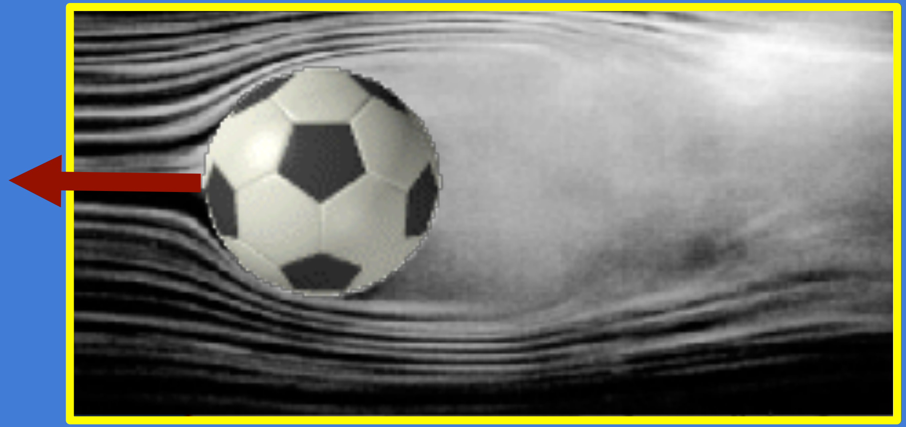


- the flow is turbulent
- vortices shed in a chaotic, unpredictable fashion

→ the ball moves erratically

The flow around a soccer ball without spin





- the flow is turbulent
- vortices shed in a chaotic, unpredictable fashion

$\longrightarrow$ the ball moves erratically


COLO COLO 0 1 SANTOS 4:36
sports
VIVO
VISA VISA VISA VISA


COLO COLO
0 1
SANTOS
4:36
VIVO
VISA

Anomalous curvature of sports balls: the Magnus effect

Anomalous curvature of sports balls: the Magnus effect


SHOW
GS 2 - 2 V. REAL
collezione collezione collezione
KEBANPEN KEBANPEN
GURAL
Galatasaray.org

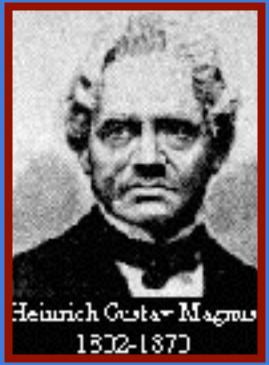

SHOW
GS 2 - 2 V. REAL
collezione collezione collezione
KEBANPEN KEBANPEN
GÜRAL
Galatasaray.org

Backspin flattens out the trajectory via Magnus lift.

Backspin flattens out the trajectory via Magnus lift.

History of the Magnus Effect

- Sir Isaac Newton (1672) noted how a tennis ball's flight was influenced by spin



- Robin (1742, no portrait available), a British artillery sargent, studied the anomalous flight of spinning cannon balls
- Heinrich Gustav Magnus (1802-1870), physicist and chemist at University of Berlin, examined the lateral force on rotating cylinders in air currents

- Lord Rayleigh considered inviscid theory, and demonstrated that the sideways force on a spinning, translating ball is proportional to its speeds of translation and rotation

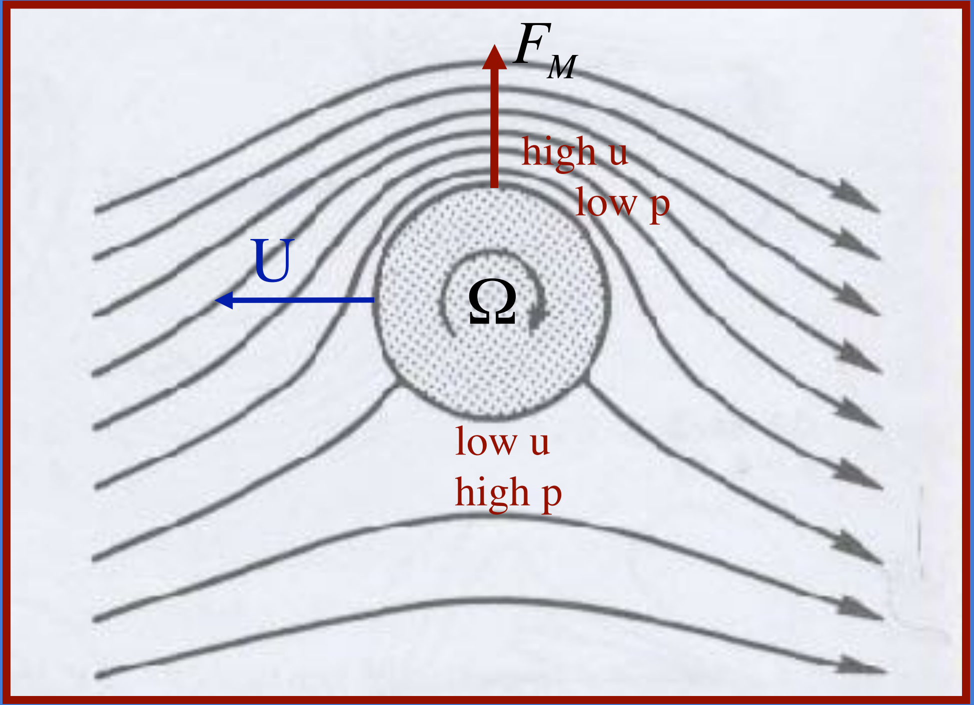
- Ludwig Prandtl (1904) developed classical boundary layer theory, a crucial component in understanding the anomalous flight of balls in flight

The translation of a spinning sphere

Two dimensionless groups:

$$Re = \frac{U a}{\nu}$$

$$\frac{\Omega a}{U} = \frac{\text{rotational speed}}{\text{translational speed}}$$



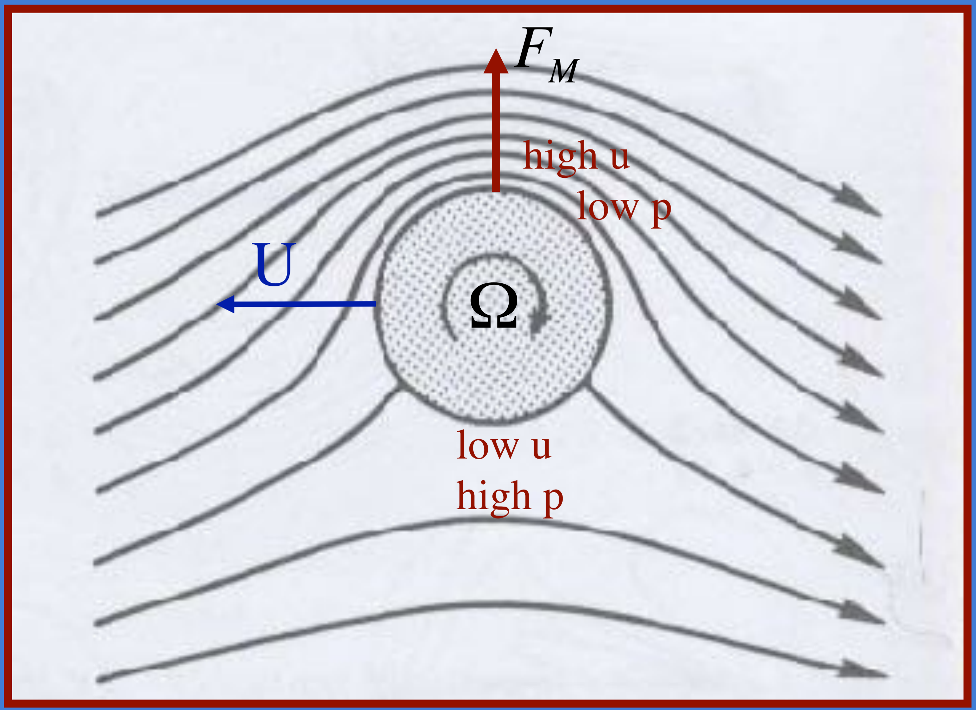
The Magnus Effect

- a consequence of the asymmetry in the pressure distribution
- Magnus force:

$$\boxed{F_M = C_L\left(\frac{\Omega a}{U}, \frac{U a}{\nu}\right) \rho \, a \, U \, \Omega}$$

- applications: ballistics, sports balls, other…

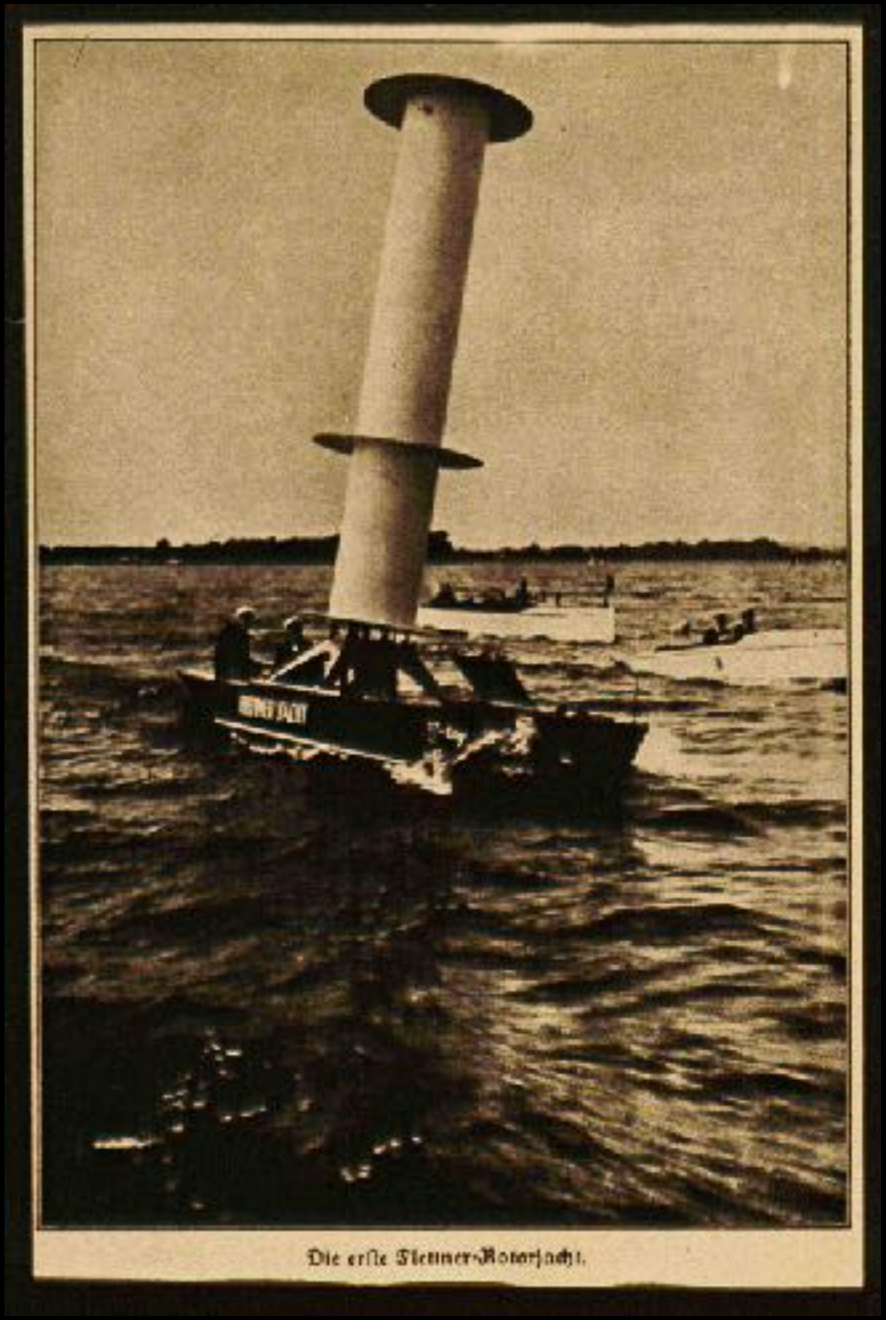
The Magnus force in ballistics



- bullets and shells are spin-stabilized to keep them from tumbling in flight
- a cross wind will induce a Magnus force than will alter the trajectory
- must be corrected for by skilled snipers

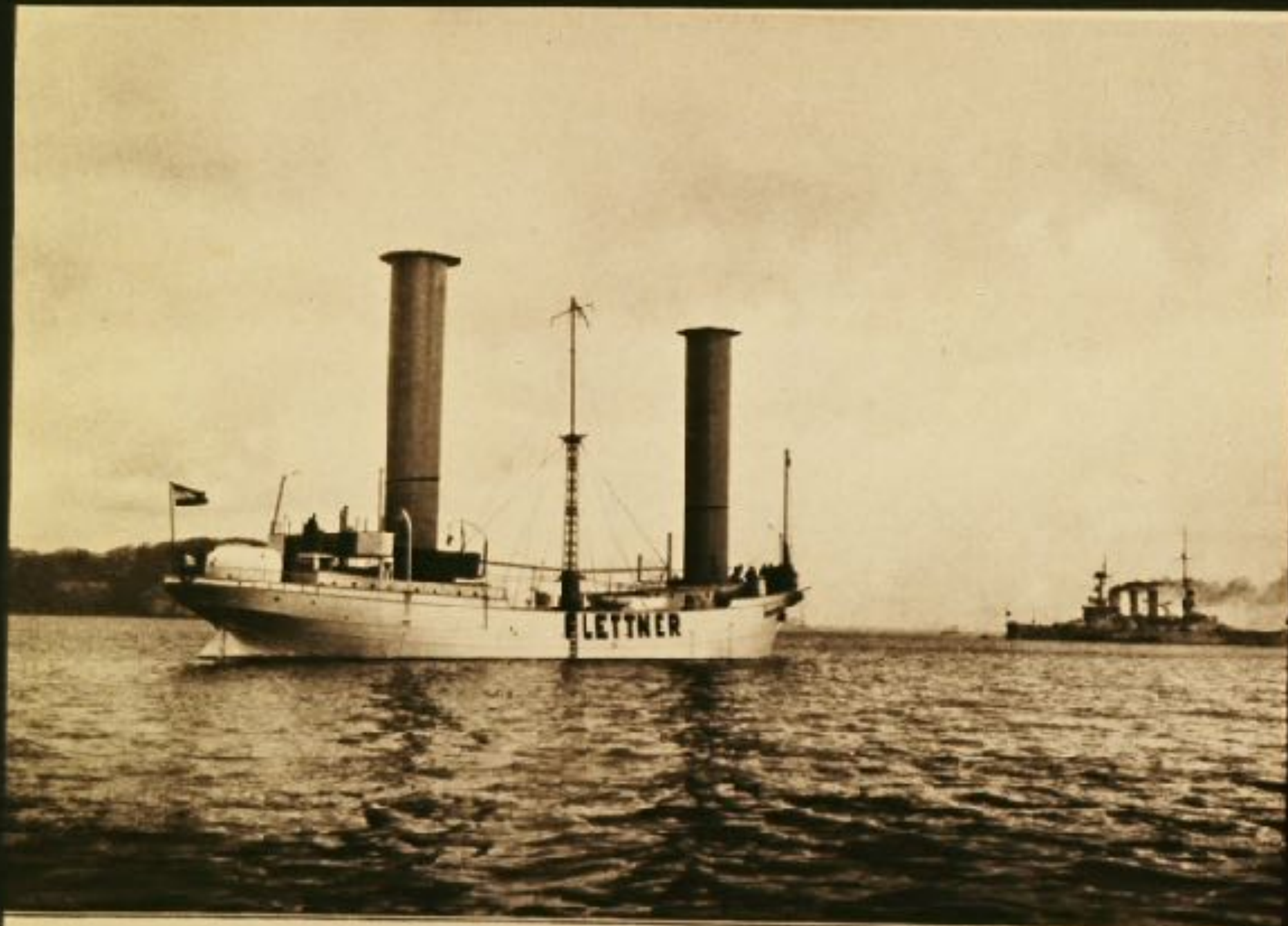
Magnus Sailboats

- sail replaced by rotating cylinder
- cylinder driven by motor powered by generator: energy derived from wind
- successfully circumnavigated the world
- less efficient that traditional sailboats or motorboats



Die erste Flettner-Rotorjacht.

n = 2



Abfahrt der „Baden-Baden“ nach Amerika.

n = 3

(by Courtesy of James Howden & Co., Ltd., Glasgow.

THE ROTOR MOTORSHIP 'BARBARA' ON TRIAL. *An application of the Magnus effect—see Chapter IX.*

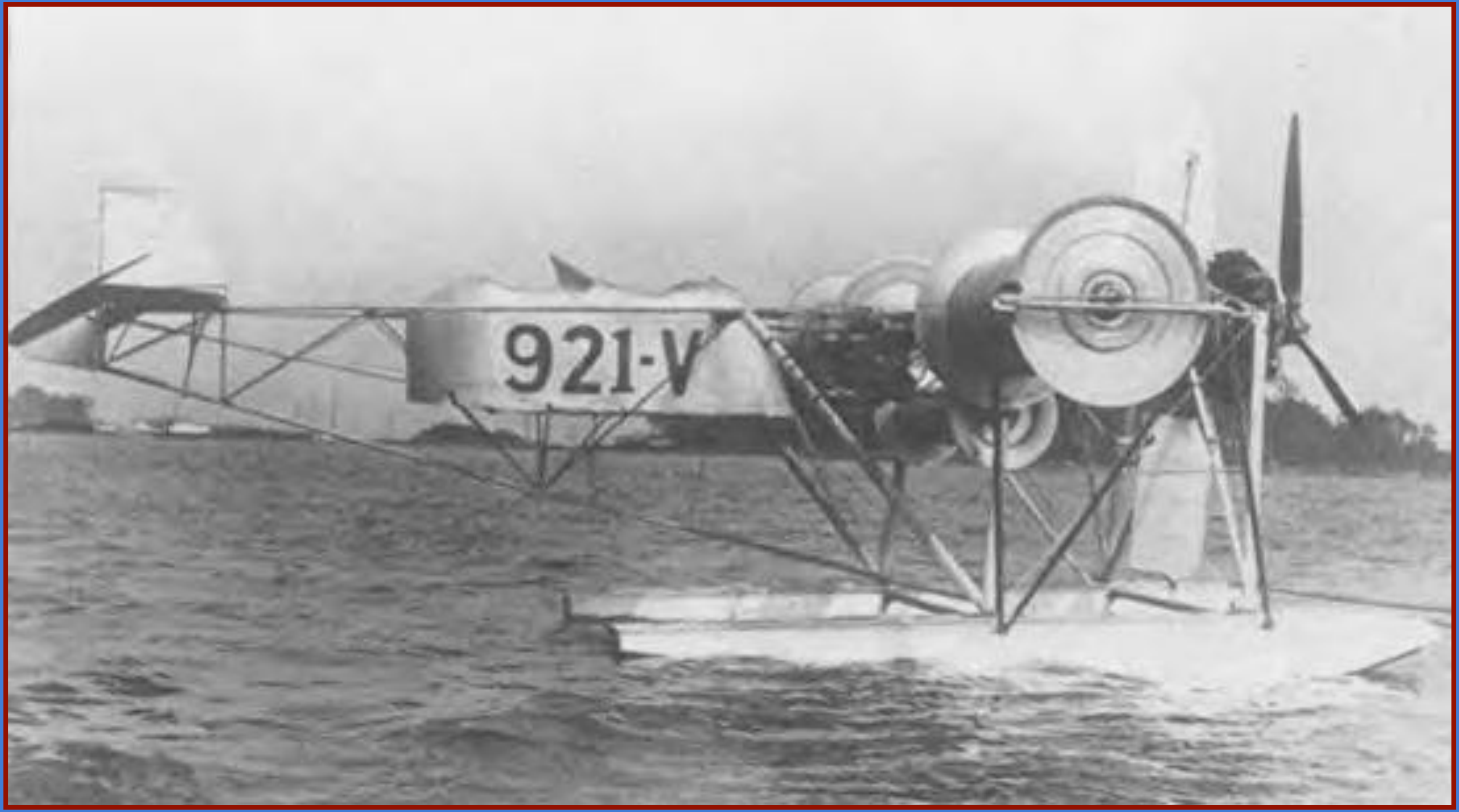
A modern Magnus ship

Magnus airplanes

- four conical rotors in an open frame replace the wing
- the designer claimed it had double the lifting power of conventional wings

- there is no record of its having successfully flown
- overcoming the bluff body drag on wings is the principal difficulty

Magnus airplanes



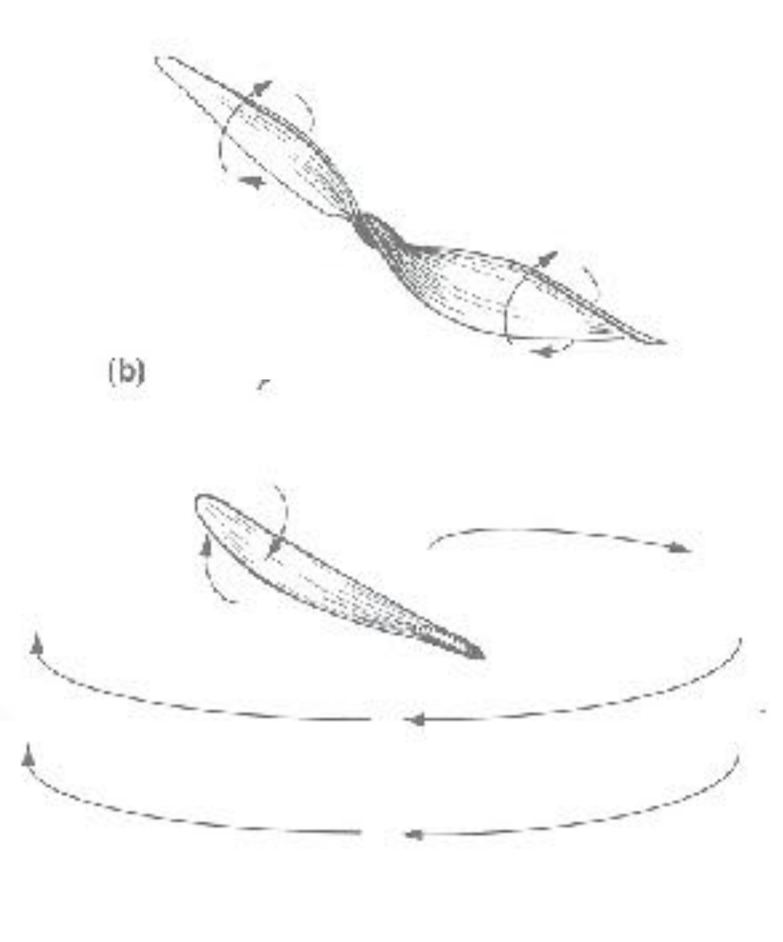
- three horizontal spinning cylinders replace the wings
- successfully flew once, but crash landed

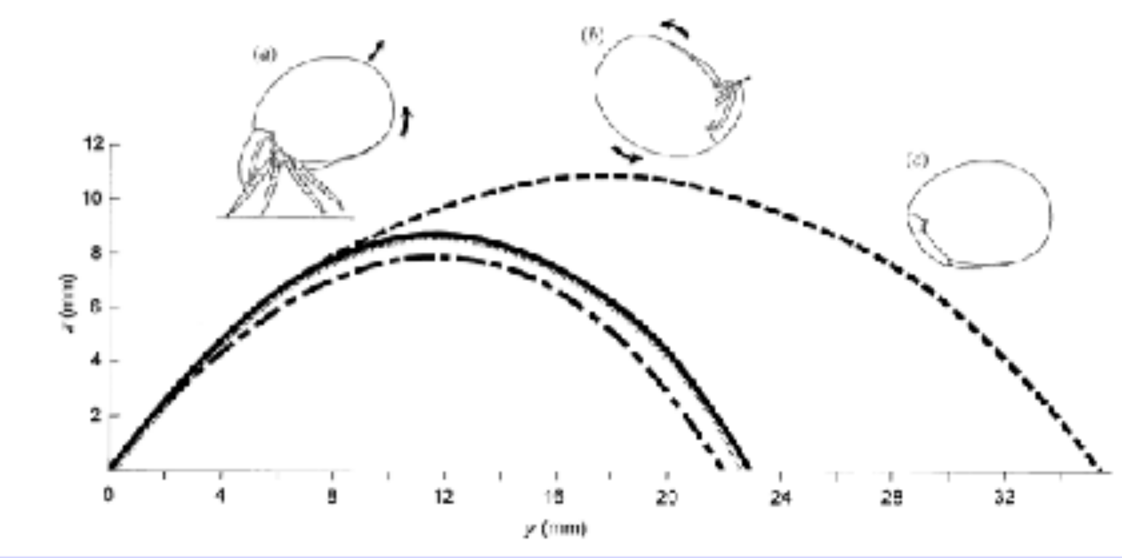
The Magnus effect in Nature

- rotation coupled with translation increases lift

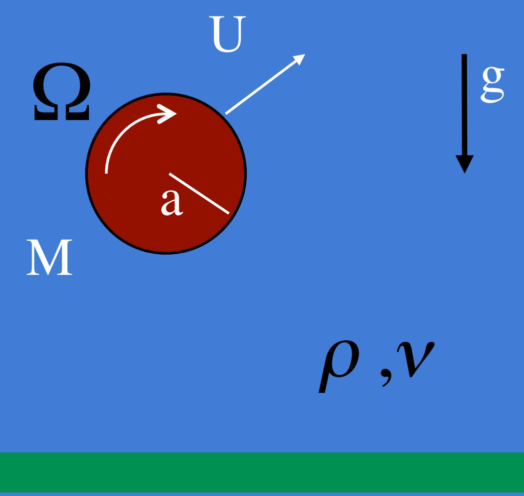
Falling seed pods

Leaping mites





Equation of motion of a ball in flight

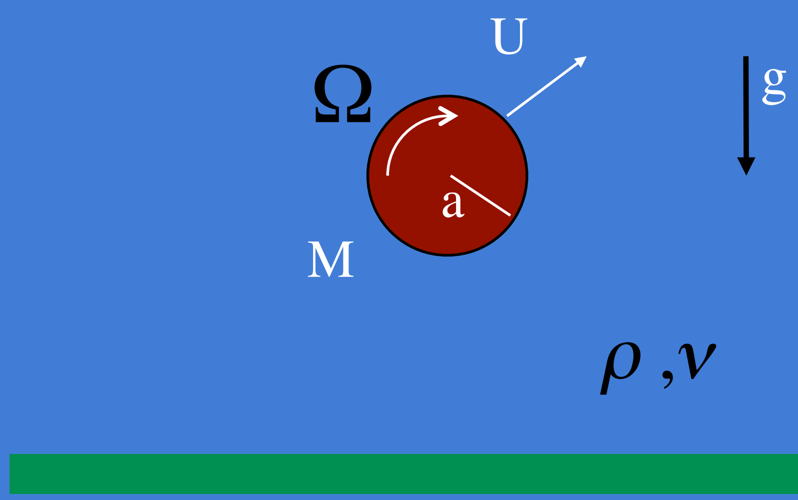


$$\boxed{m\frac{d\mathbf{U}}{dt} = m\mathbf{g} + \mathbf{F}_{aero}(Re, S)}$$

Reynolds number: $$Re = \frac{Ua}{\nu} = \frac{inertial\ \ pressure}{viscous\ \ stress}$$

Spin number: $$S = \frac{\Omega a}{U} = \frac{rotational\ \ speed}{translational\ \ speed}$$

Trajectory equation of a spinning ball

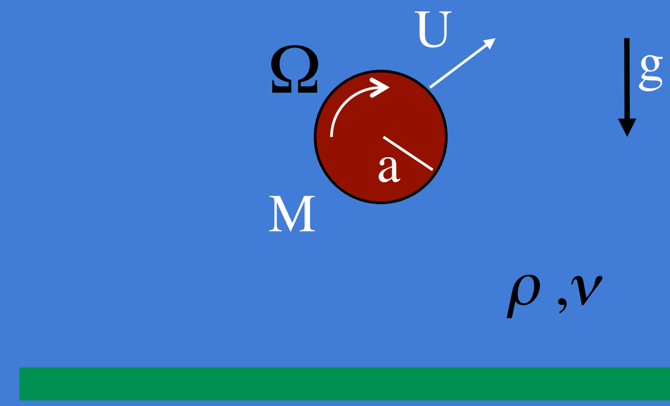


$$m\frac{d\mathbf{U}}{dt} \;=\; m\mathbf{g} \;-\; C_d\,\pi a^2 \rho\, U^2\,\hat{\mathbf{s}} \;+\; C_L\,\pi a^3 \rho\,\boldsymbol{\Omega}\times\mathbf{U}$$

AIR DRAG

MAGNUS FORCE

Aerodynamic length



- deduce length, time over which ball changes direction via scaling

$$m\frac{d\mathbf{U}}{dt} \;=\; \cancel{m\mathbf{g}} \;-\; \cancel{C_d\,\pi a^2\rho\,U^2}\;\hat{\mathbf{s}} \;+\; C_L\;\pi a^3\rho\;\boldsymbol{\Omega}\times\mathbf{U}$$

$$\rho_B V\frac{U^2}{L_a} \;\sim\; \rho V U \Omega \;\longrightarrow\; \boxed{L_a \;\sim\; \frac{U}{\Omega}\frac{\rho_B}{\rho}}$$

AERODYNAMIC LENGTH

Turning time

$$\boxed{\tau_T \sim \frac{L_a}{U} \;\sim\; \frac{1}{\Omega}\frac{\rho_B}{\rho}}$$

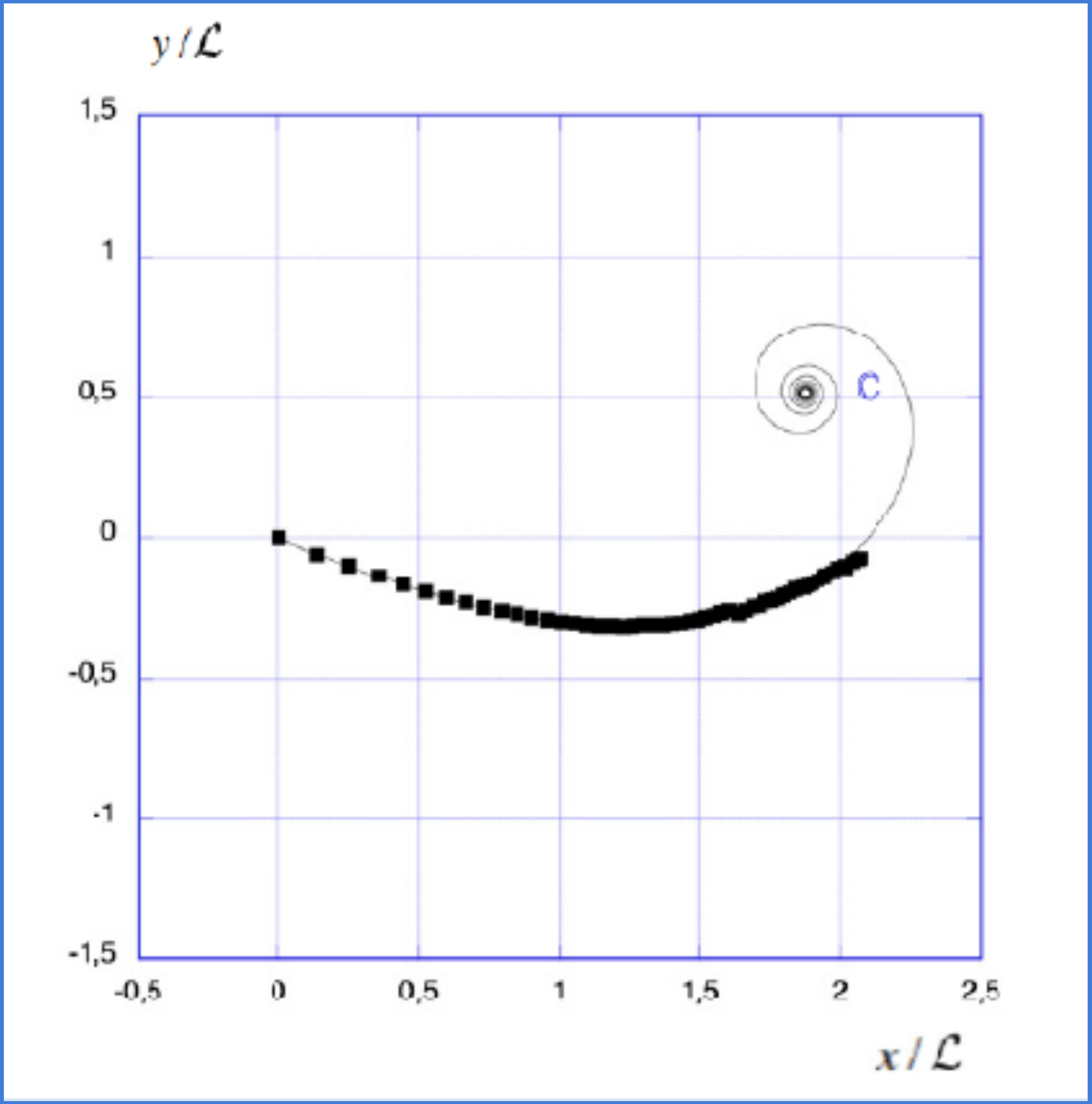
Drop a spinning basketball from a 450ft dam

- Magnus force deflects ball in a horizontal direction

Drop a spinning basketball from a 450ft dam

- Magnus force deflects ball in a horizontal direction

The logarithmic spiral arising if Ω = const



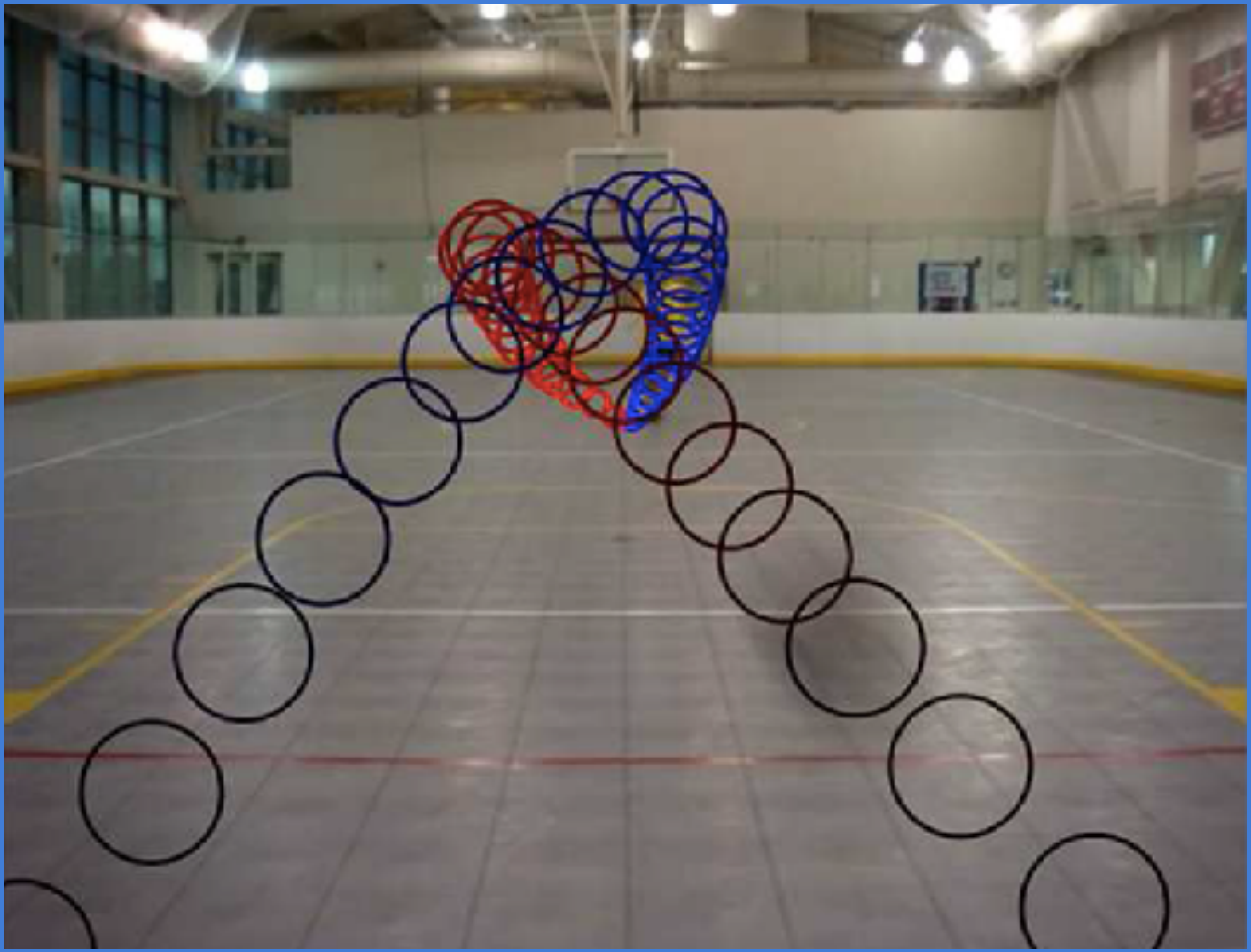
A new puzzle

- trajectories of two identical balls, one smooth, one rough

A new puzzle

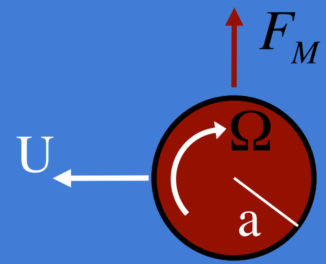
- trajectories of two identical balls, one smooth, one rough

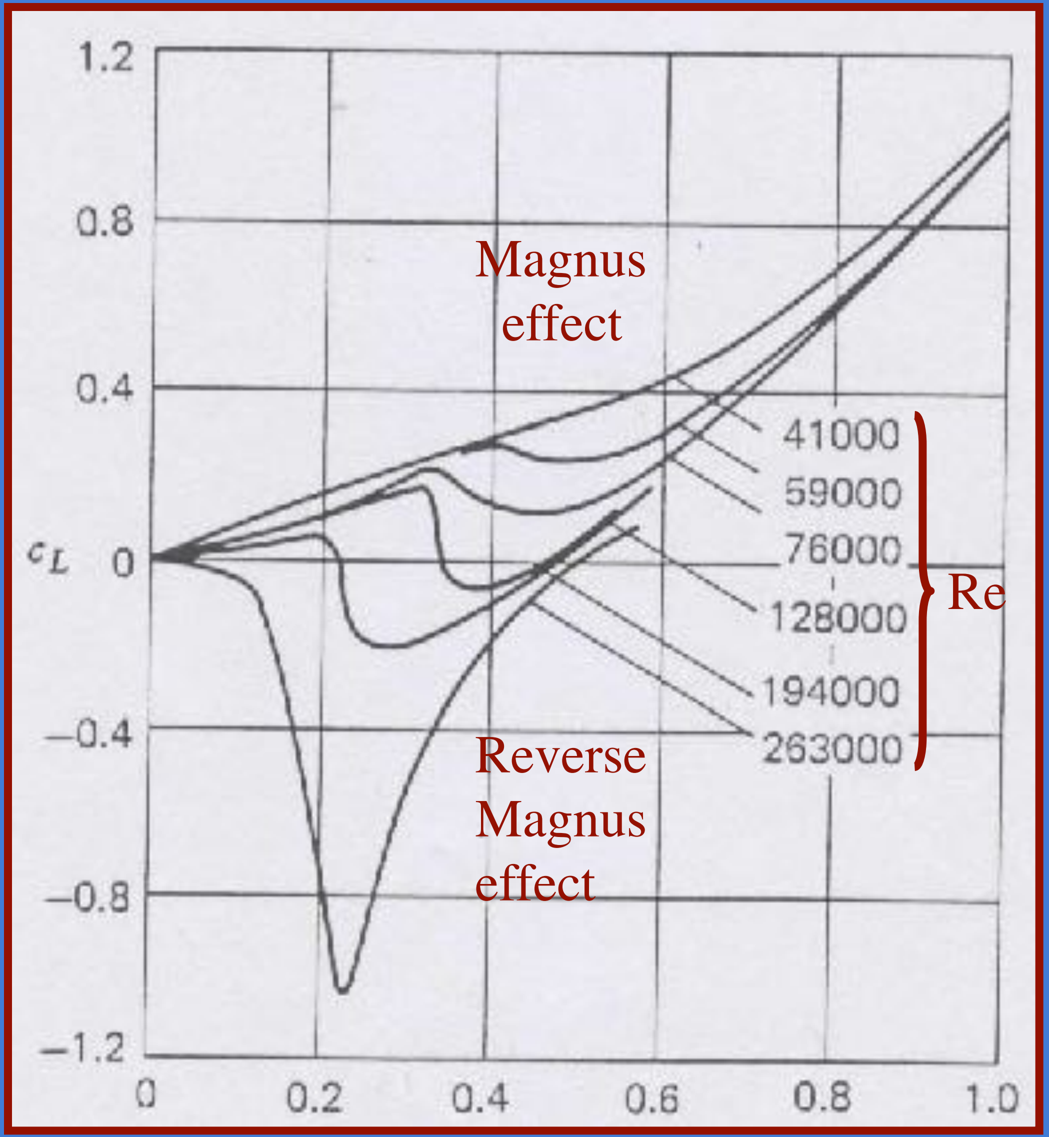
A new puzzle



- trajectories of two identical balls, one smooth, one rough

Magnus force: $F_M = C_L\left(\frac{\Omega a}{U}, \frac{U a}{\nu}\right) \rho\, a\, U\, \Omega$



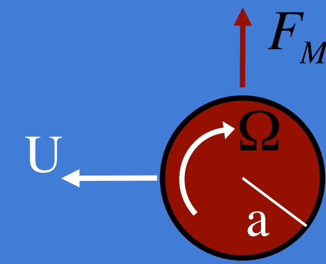


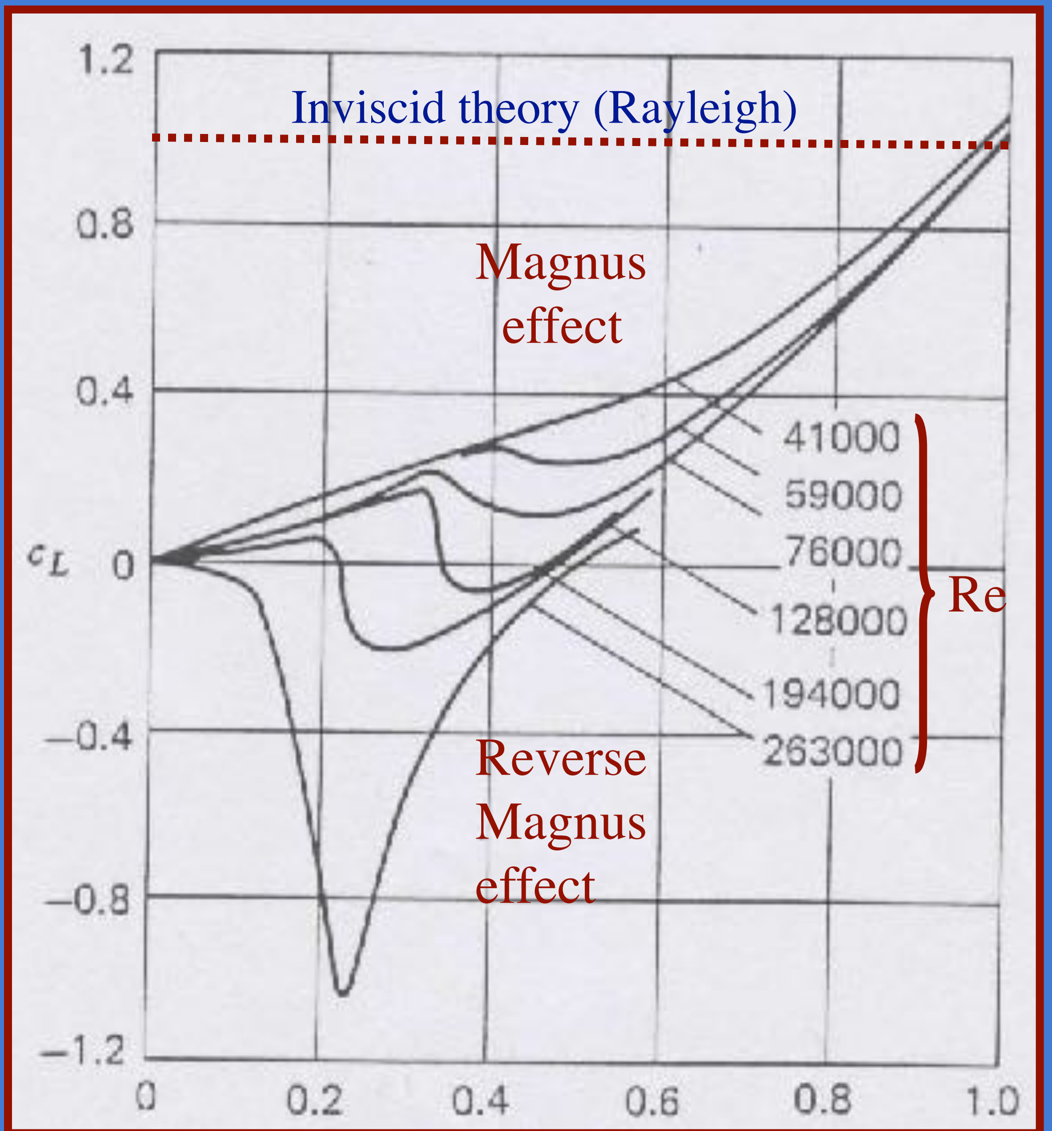
$\Omega a/U$

Important Point

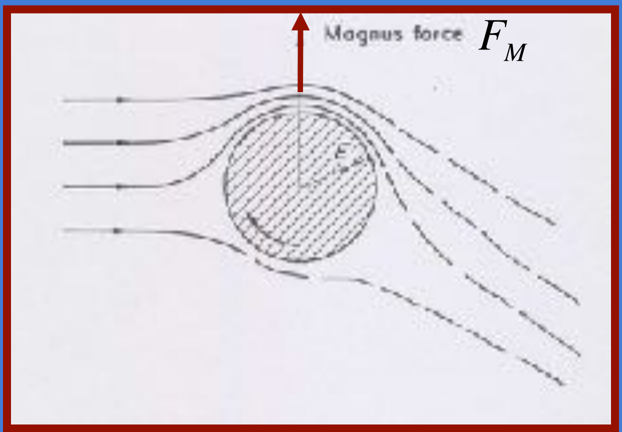
- in the absence of surface roughening, most sports balls, including soccer balls, would curve in the opposite sense!

Magnus force: $F_M = C_L\left(\frac{\Omega a}{U}, \frac{U a}{\nu}\right)\ \rho\, a\, U\, \Omega$

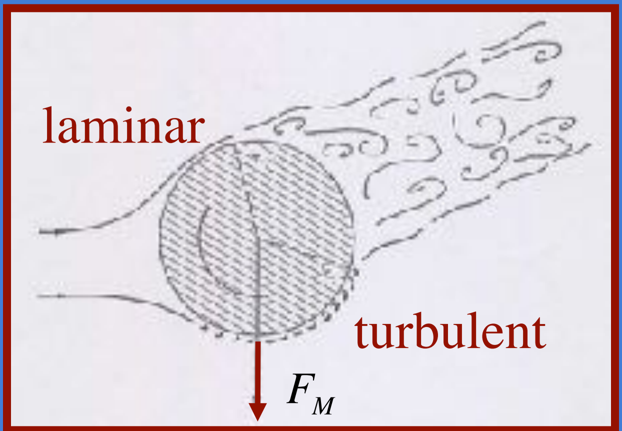




$\Omega a/U$

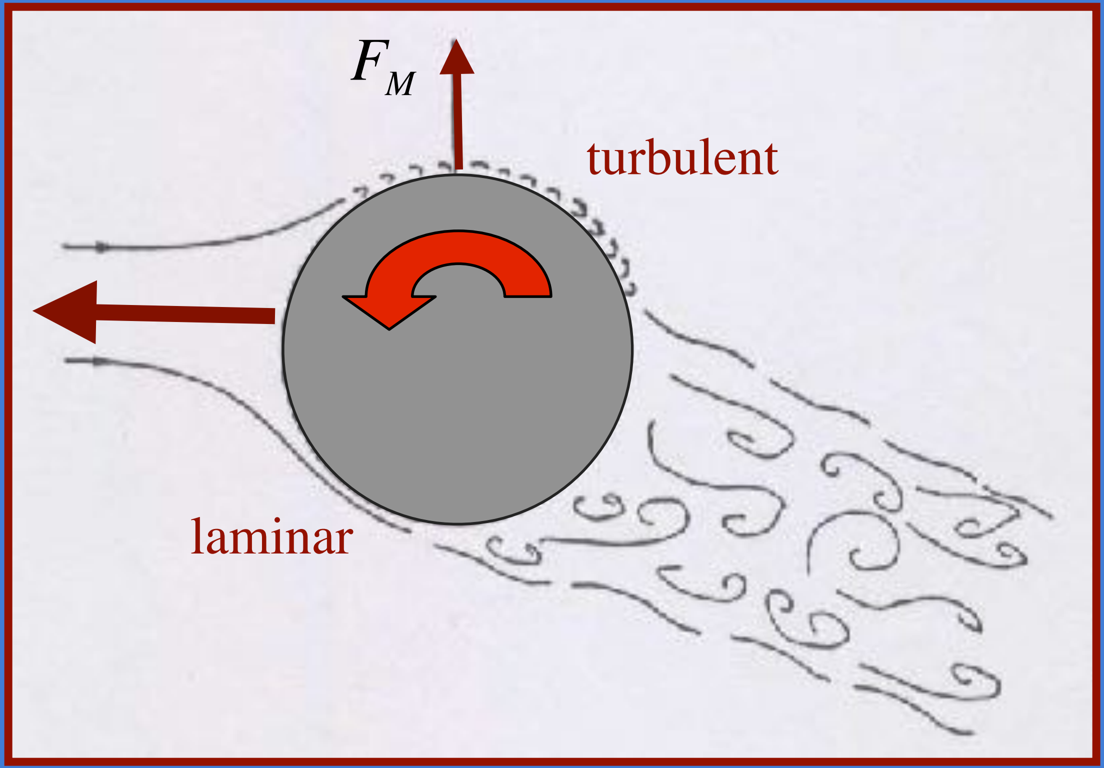


Reverse Magnus effect



The reverse Magnus Effect

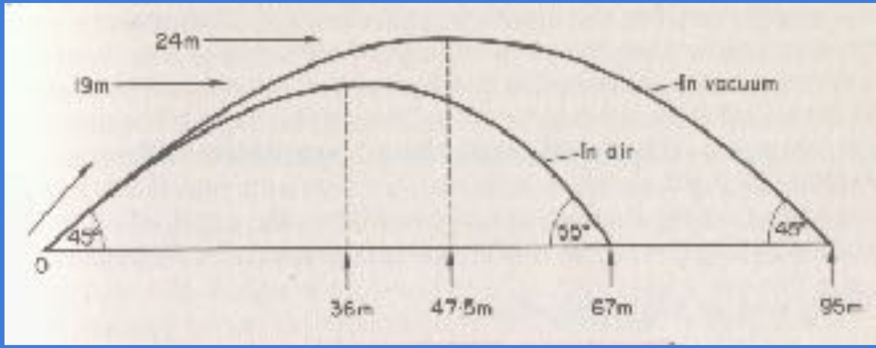
- observation: smooth soccer balls, e.g. beach balls, BEND THE WRONG WAY!



- turbulent b.l. on advancing side, laminar on retreating side
- asymmetry in pressure distribution results in negative Magnus force
- force may also be rationalized in terms of momentum transfer

Soccer/Football/Futbol

- peak $\mathrm{Re} = 425{,}000 > \mathrm{Re}_c$: supercritical drag coefficient
- seams critical in suppressing reverse Magnus effect
- shots generally pass from supercritical to subcritical drag during flight: decelerate drastically at end
- Magnus effect used in crossing (chipping) and shooting (`bending the ball')



Conditions	Distance travelled by goal kick
In vaccum	125 m
At sea-level	60 m
Subcritical drag coefficient	40 m
At 2.2km altitude	65 m

- altitude: in Mexico City (at 2.2 km), $\rho = 0.8\,\rho_{sea-level} \longrightarrow D \sim \rho\, U^2 a^2$ decreased
- a 25m shot arrives 0.02 s sooner, in which time goalie diving at 10m/s covers 20cm

The influence of surface roughness

- can cancel or even reverse the sign of the Magnus force

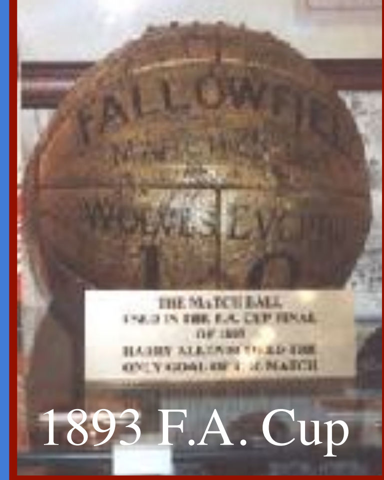
- trajectories of two identical balls, one smooth, one rough

The influence of surface roughness

- can cancel or even reverse the sign of the Magnus force

- trajectories of two identical balls, one smooth, one rough

1863



1893 F.A. Cup

1910

1929

1930 World Cup

1937

1945

1948

1950

1963

1970 World Cup

Modern

Modern

The lexicon of Brazilian free kicks

1. Chute de curva: Banana kick
   - struck with instep; inward bending
2. Folha Seca: The Dry Leaf
   - struck with instep/top of foot with topspin; downward dipping
3. Pombo sem asas: Dove without Wings
   - struck with top of foot with no spin; erratic trajectory
4. Tres dedos/Trivela: Three Toes
   - struck with outside of foot; outward bending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all-sports
GAS HD


MUTV
GAS HD

Juninho

Juninho

Brazilian free kicks

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Folha Seca

- invented by brazilian great Didi (WC 1954. 1958, 1962)

Juninho Pernambucano

Folha Seca

- invented by brazilian great Didi (WC 1954. 1958, 1962)

Juninho Pernambucano

Folha Seca

Juninho Pernambucano

Folha Seca

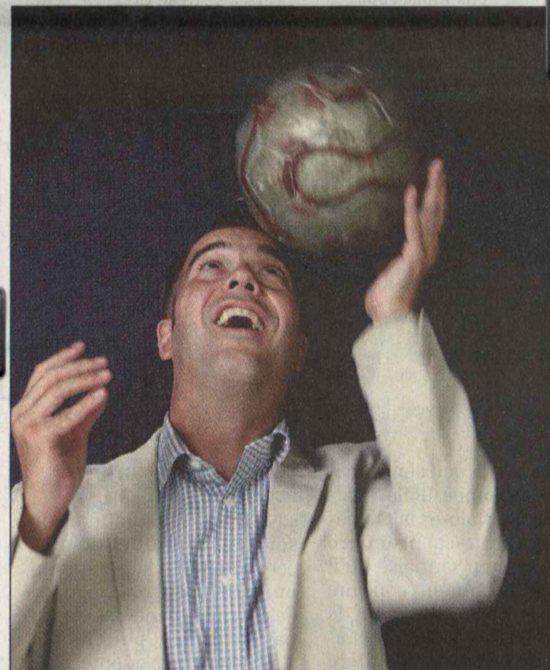
Juninho Pernambucano

LES CHERCHEURS S'INTÉRESSENT AU PHÉNOMÈNE JUNINHO

« Juni », une science exacte

Magique ou scientifique ? Un Canadien s'est penché sur le cas des coups-francs du Brésilien

De Junhino, on croyait tout savoir et tout avoir déjà dit. C'était avant d'apprendre que ses coups-francs n'ont rien de magique, mais tout de scientifique. Et d'ailleurs, ils permettent à la science d'avancer.
C'est un ponte qui le dit, il est Canadien et s'appelle Bush, John W. Bush. Un mythe dans son domaine, et son domaine c'est justement le MIT (Mas- dans notre domaine » explique John W. Bush. Ce type, qui est donc une sorte de Zidane de la mécanique des fluides (on dit Zidane, mais on aurait pu dire Platini ou Juninho) a aussi été étudiant, et avait commencé ses études en se posant cette question à propos des footballeurs brésiliens : « mais comment font-ils pour réussir à donner ces courbes au ballon » ?



John W. Bush a beau essayer, il aura du mal à rivaliser avec l'objet de son étude / Photo Philippe Juste

qui me permet de frapper le ballon comme lui. Ni, si j'étais gardien de but, à me permettre de les arrêter ».

On avait eu peur de tomb[...] sur un type qui ramène s[...] science, une sorte de paricid[...] du Père Noël, on dit ça pou[...]

The Zidane of Fluid Dynamics Tries to Explain Why a Ball Curves

ARTICLE | COMMENTS (4)

BEND CURVE DAVID BECKHAM FREE KICK JONES MATH SOCCER

Email Print

By WILL CONNORS

Wall Street Journal, June 2014

United States' Jermaine Jones celebrates with his teammates after scoring against Portugal at the World Cup —Associated Press

RIO DE JANEIRO When Jermaine Jones scored his ripper of a goal in the U.S.'s second World Cup game against Portugal, John Bush celebrated along with millions of Americans. He also took note of how the ball curved around a Portuguese defender.

"It would definitely have gone wide had it followed its initial trajectory," Mr. Bush says.

Mr. Bush is a professor of applied math and fluid dynamics at MIT. He's also a big soccer fan, and he'd like the world to understand a bit more about how a soccer ball moves through the air.

Brazilian free kicks

1. Chute de curva: Banana kick
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The dove without wings: struck with no spin

C. Ronaldo

The dove without wings: struck with no spin

C. Ronaldo

Brazilian free kicks

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Pele, 1970 World Cup

Pele, 1970 World Cup

Nilinho

Nilinho

El segundo mejor tiro de la historia

Roberto Carlos, Tournoi de France 1994

El segundo mejor tiro de la historia

Roberto Carlos, Tournoi de France 1994

Why not Italian free kicks?

Why not Italian free kicks?

Why not BRITISH free kicks?

Why not BRITISH free kicks?

Why not British free kicks?

1. British football is rubbish.

2. Influence of rain on ball

   Heavier ball has higher Ballistic Coefficient , $BP = M/a^2$, and so moves less under the influence of anomalous aerodynamic forces, specifically Magnus forces.

   e.g. more difficult to `hang up' chips with slice,
   more difficult to bend free kicks

3. Balls are often overpumped

   - contact time diminished: less time to impart spin

Impact

with Christophe Clanet, Thomas Giraud

- ball has an elastic shell whose tension increases with internal pressure
- tension of ball determines duration of contact time
- duration of contact time determines the control one has in shooting

The ball strike

(Shinkai et al. 2007)

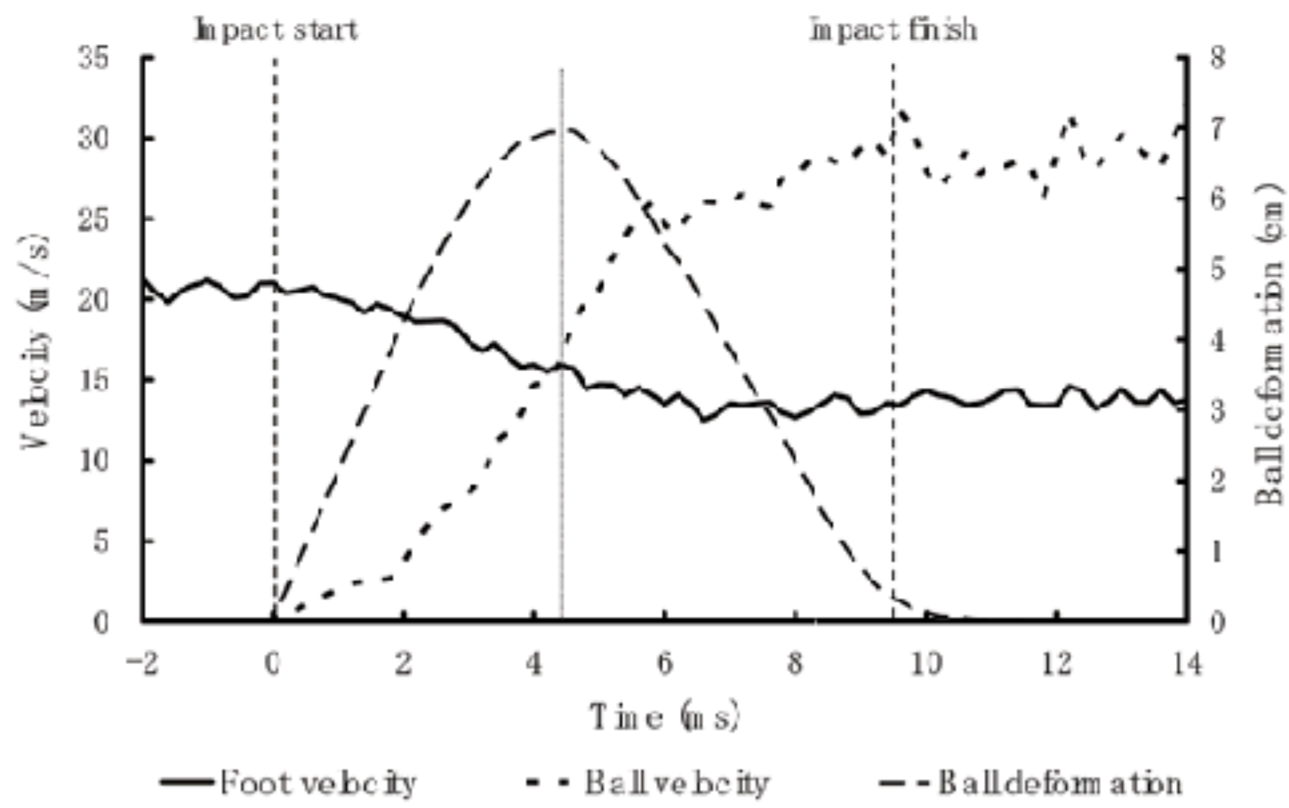
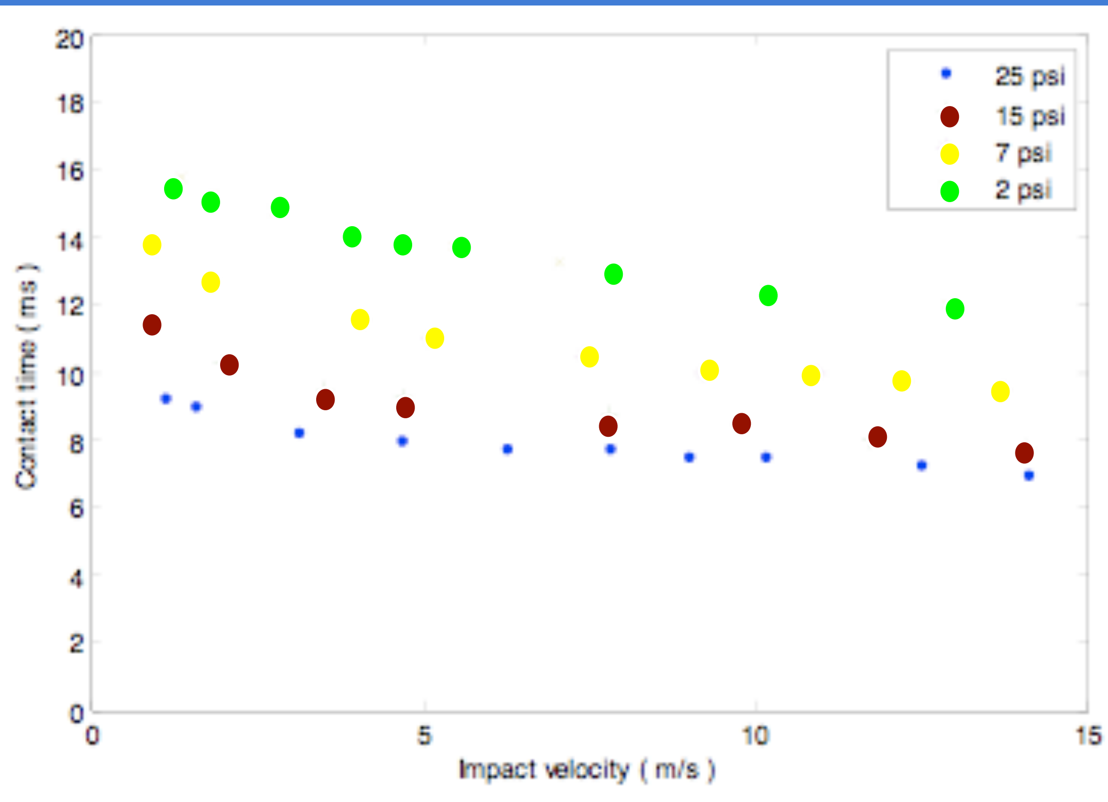
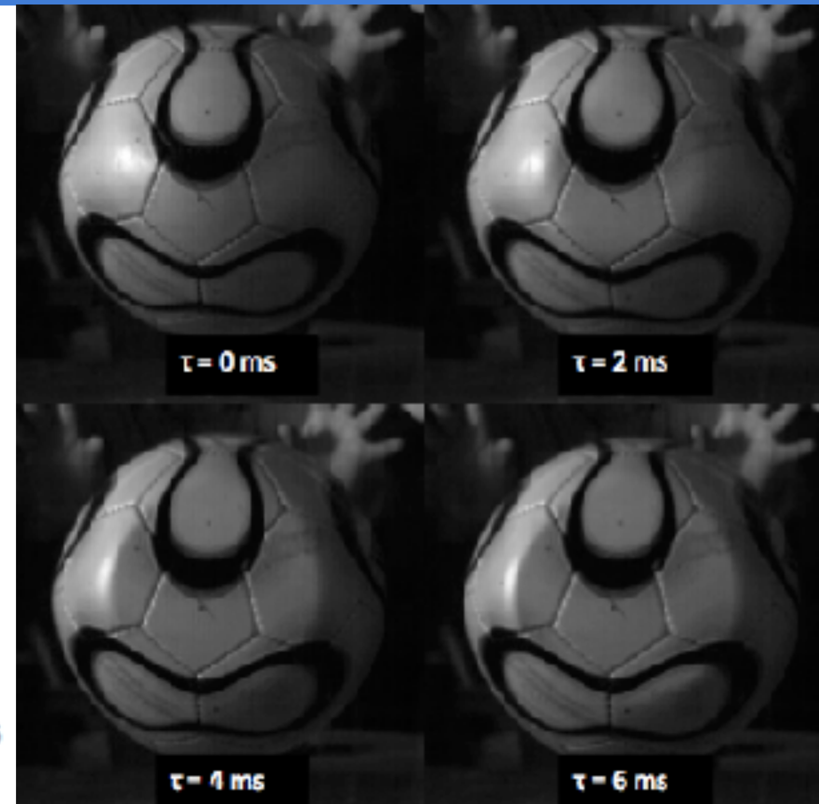


Figure 1. Foot velocity, ball velocity and ball defomation during ball impact.

- FIFA stipulates internal overpressure range of 8.7-16psi (0.6-1.1 atm)
- what role might this pressure range have on impact?
- impact time decreases by 20% over permissible pressure range

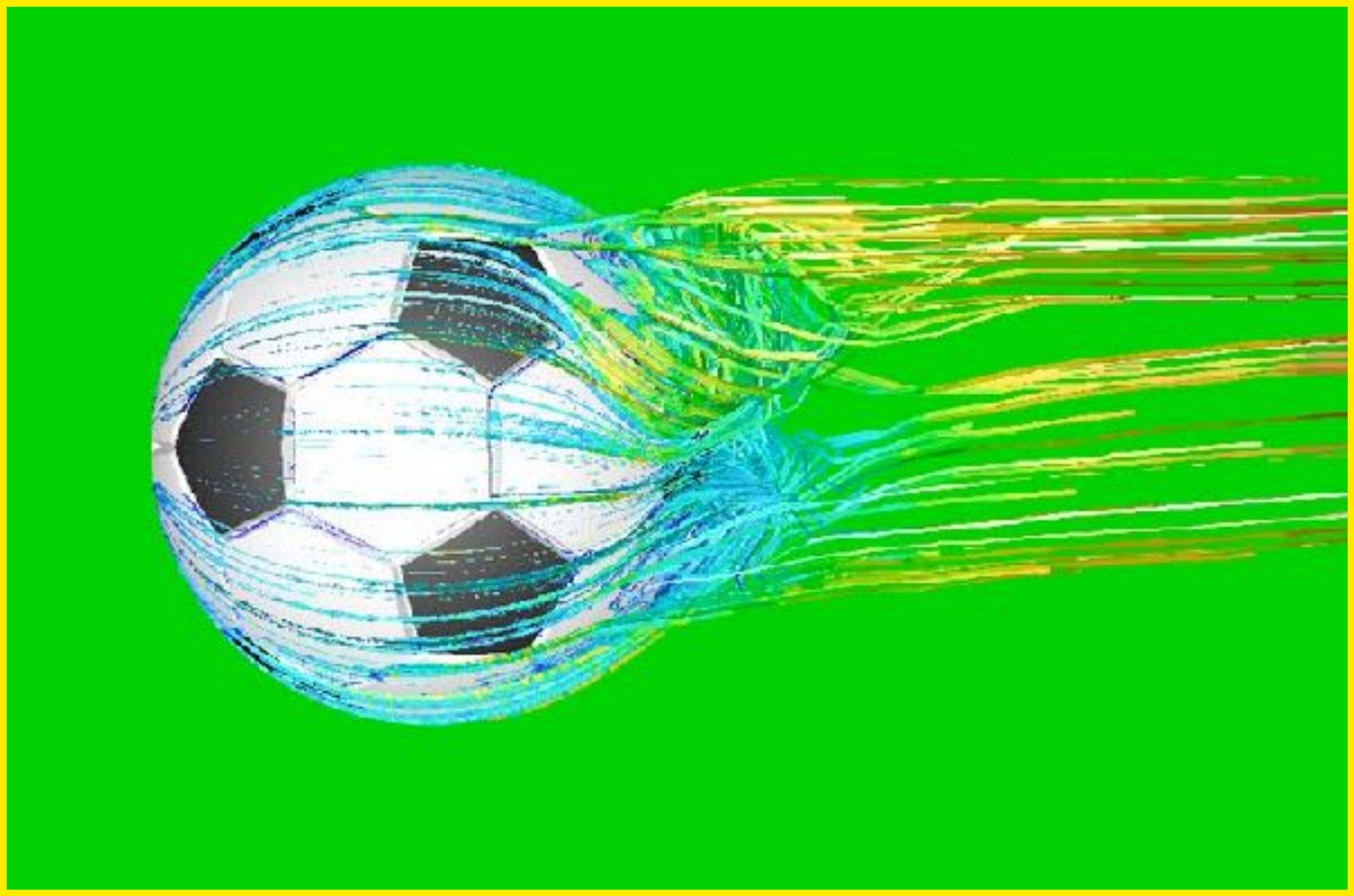
Dependence of contact time on internal pressure





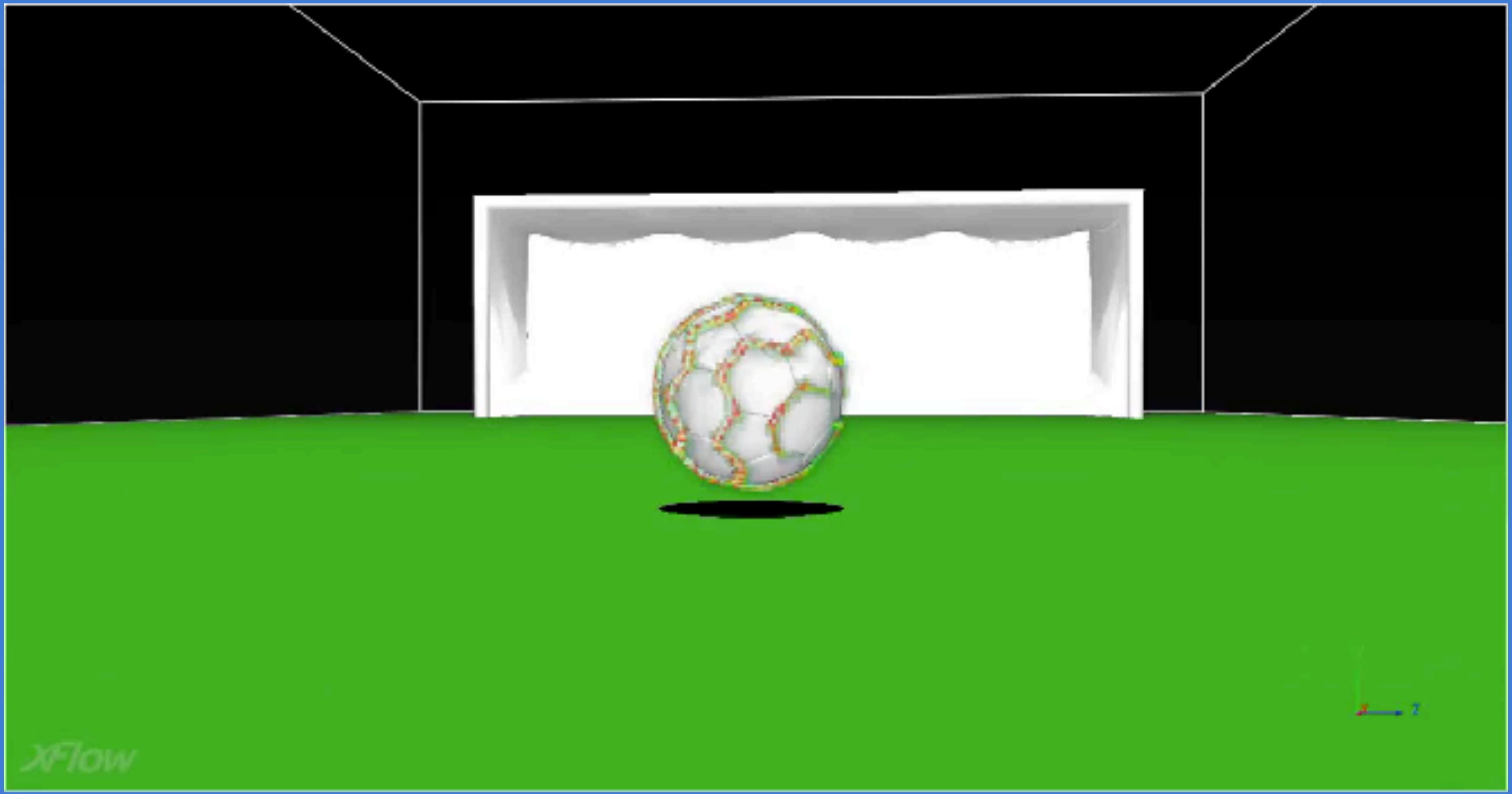
- impact time decreases by 20% over permissible pressure range
- better control (longer contact time) at lower pressure
- lower pressure ball favors more skillful players
- valve orientation significant: contact time less for strike on the valve
- folha seca favored at high pressure, with valve facing strike

Computational Fluid Dynamics: FLUENT



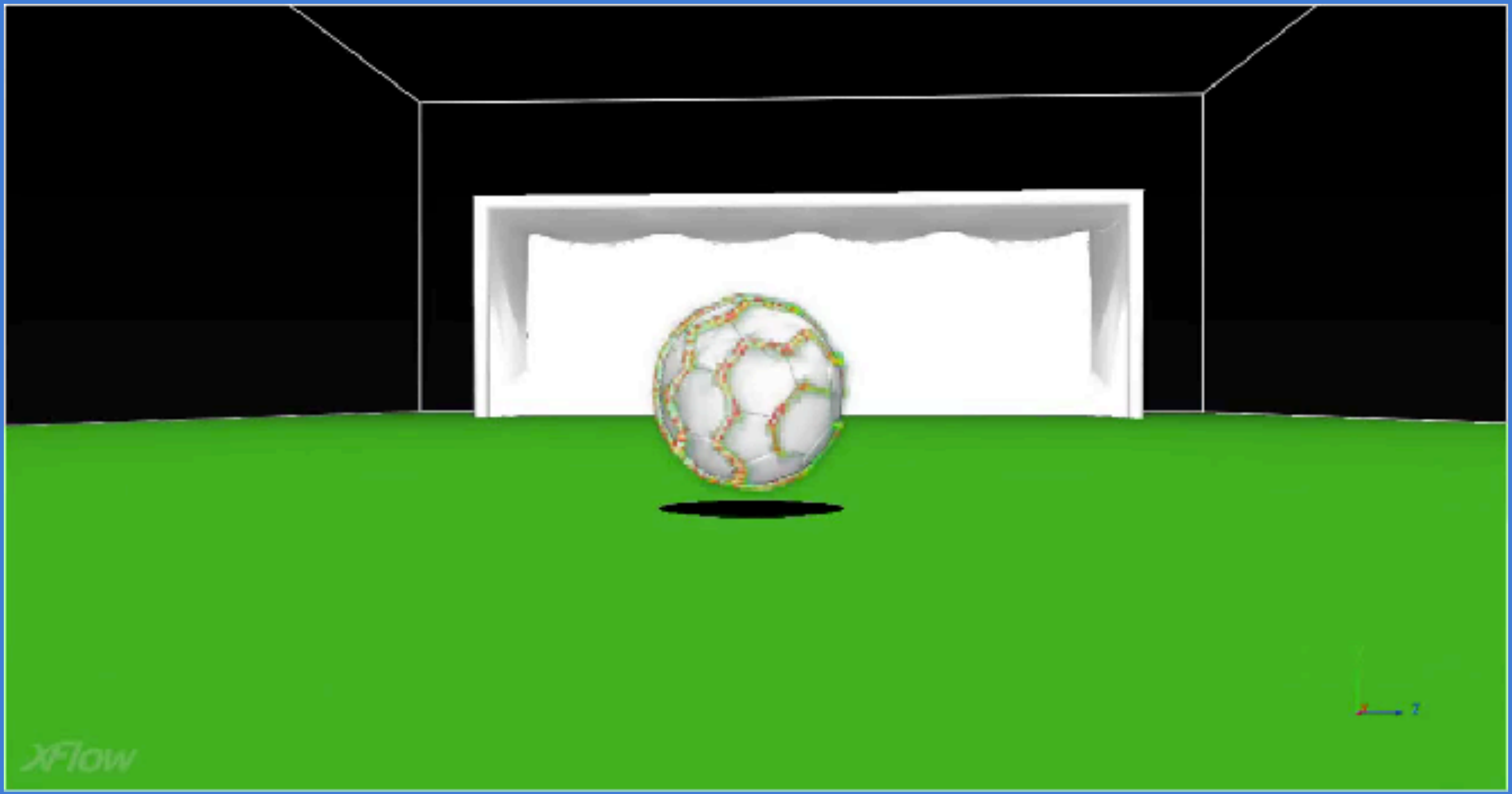
- can calculate flow around ball and associated pressure distribution
- the resulting drag and lift may be used to calculate the ball's trajectory

The flow around a spinning ball in flight



- here, fluid is thrown to the left, so the ball bends to the right

The flow around a spinning ball in flight



- here, fluid is thrown to the left, so the ball bends to the right

Bend it like Beckham

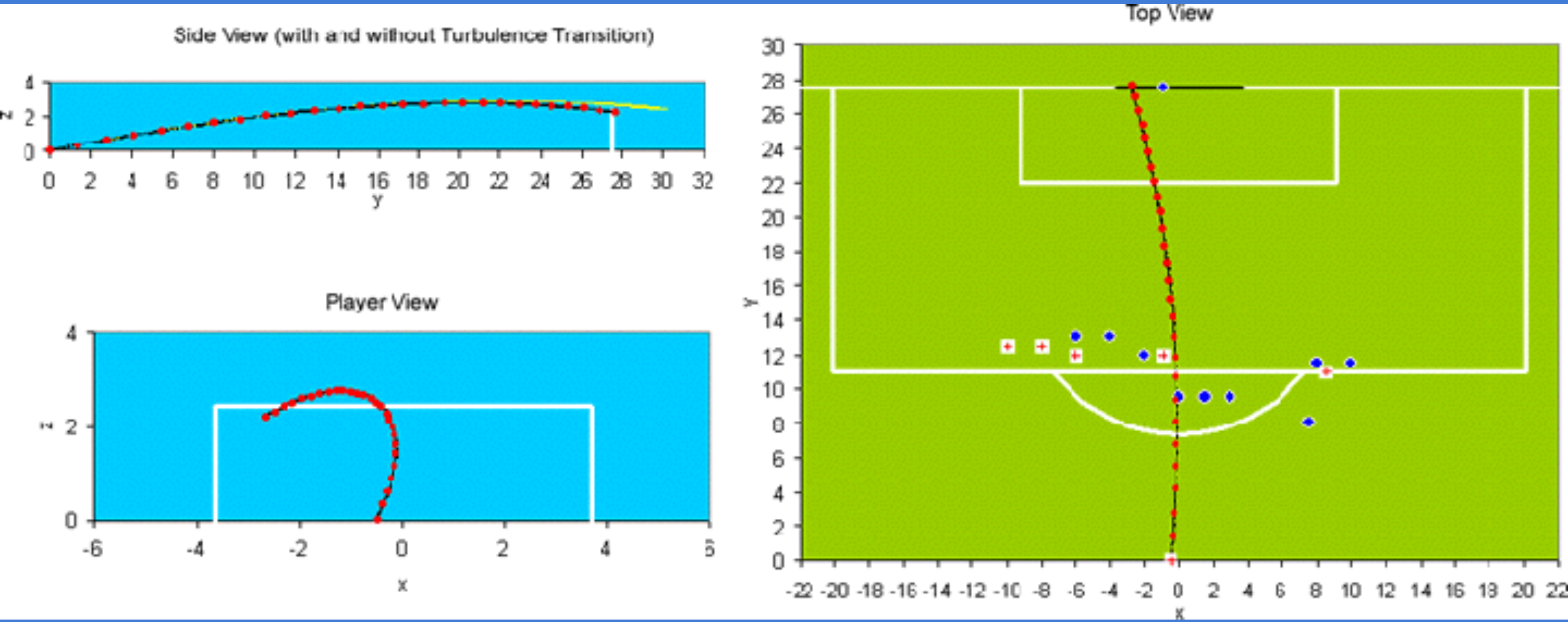
L’effet Magnus aide Angleterre à se qualifier pour la Coupe du Monde.

Bend it like Beckham

L’effet Magnus aide Angleterre à se qualifier pour la Coupe du Monde.

- given initial conditions (linear and angular velocity), can compute free kick trajectory

- transition to laminar boundary layer slows ball, causing it to dip, swerve near goal



A consulting gig…

- develop a football with more aerodynamic action
- suitable for futsol or beach football

A consulting gig…

- develop a football with more aerodynamic action
- suitable for futsol or beach football

Other sports…

TENNIS

- $Re = 122{,}000 < Re_c$; however, fuzz trips boundary layer, so turbulent drag coefficient applies

Topspin

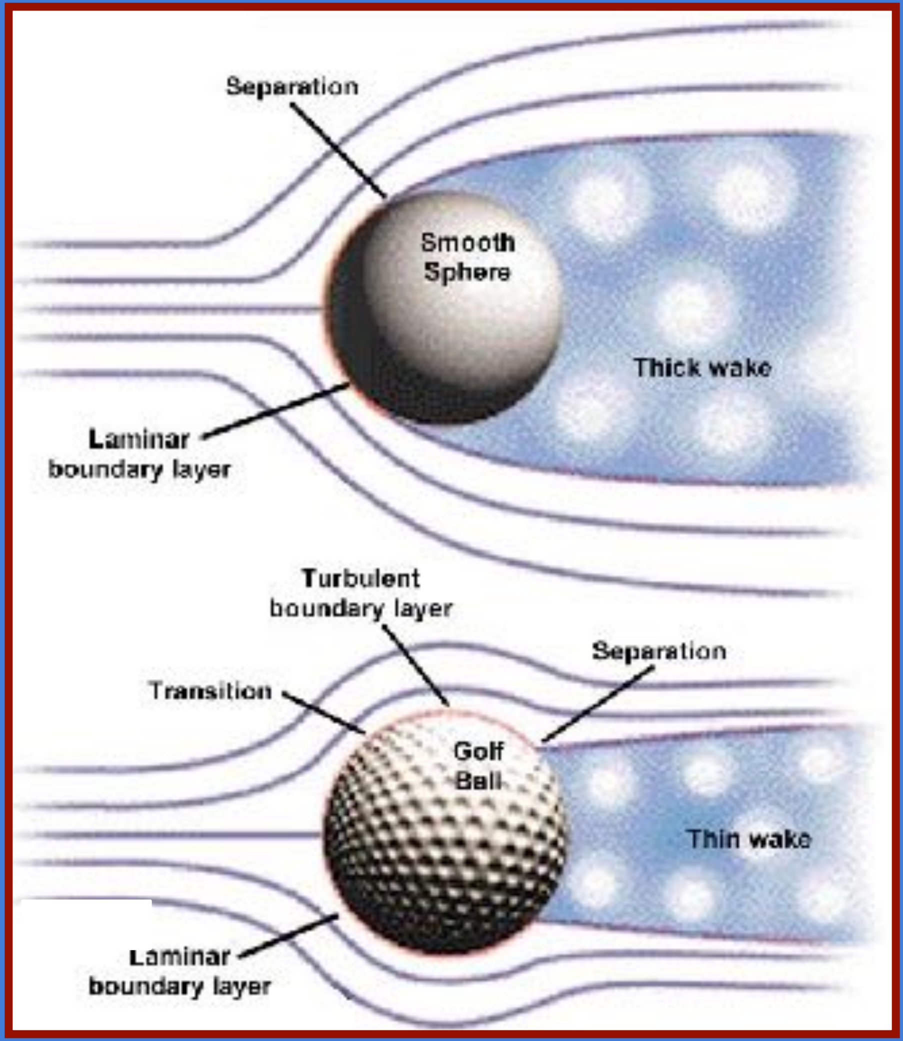
- ball deflected downward by Magnus effect
- can strike the ball with greater force and keep it in play
- ball strikes ground at large angle and `kicks up'

Slice

- ball struck with backspin, deflected upward by Magnus effect
- ball's trajectory flattened out
- ball appears to slide on impact

Golf

- $\text{Re} = 79{,}000 < \text{Re}_C$; however, dimples promote turbulent exchange between boundary layer and external flow, and so reduce drag dramatically

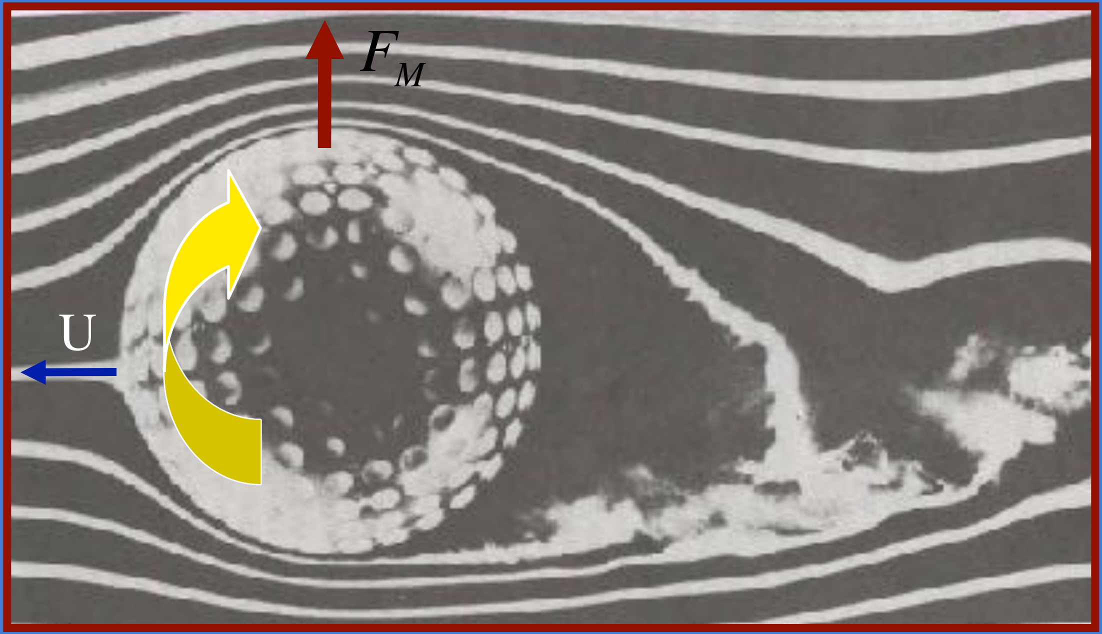


- average drive imparts backspin at rate 50-130 rev/s: Magnus force drastically increases lift

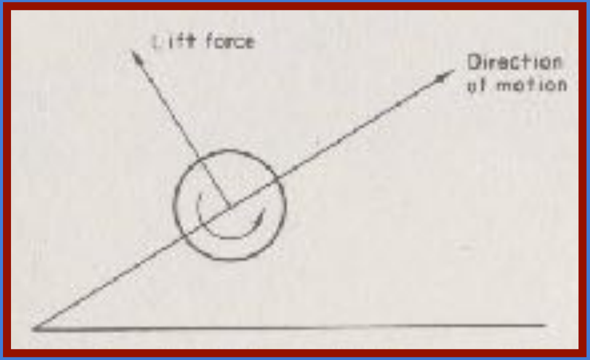
- older balls are smoother: less lift

- damaged balls: asymmetric boundary layer separation, wonky trajectory

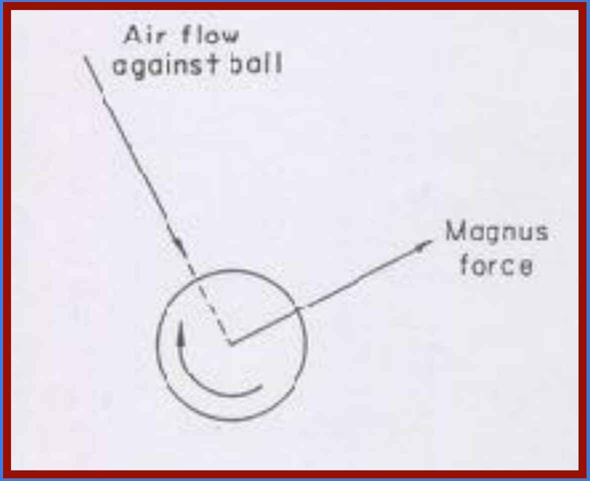
Conditions	Drive distance
Dimpled ball with backspin	230 m
Dimpled ball without backspin	100 m
Smooth ball	50 m

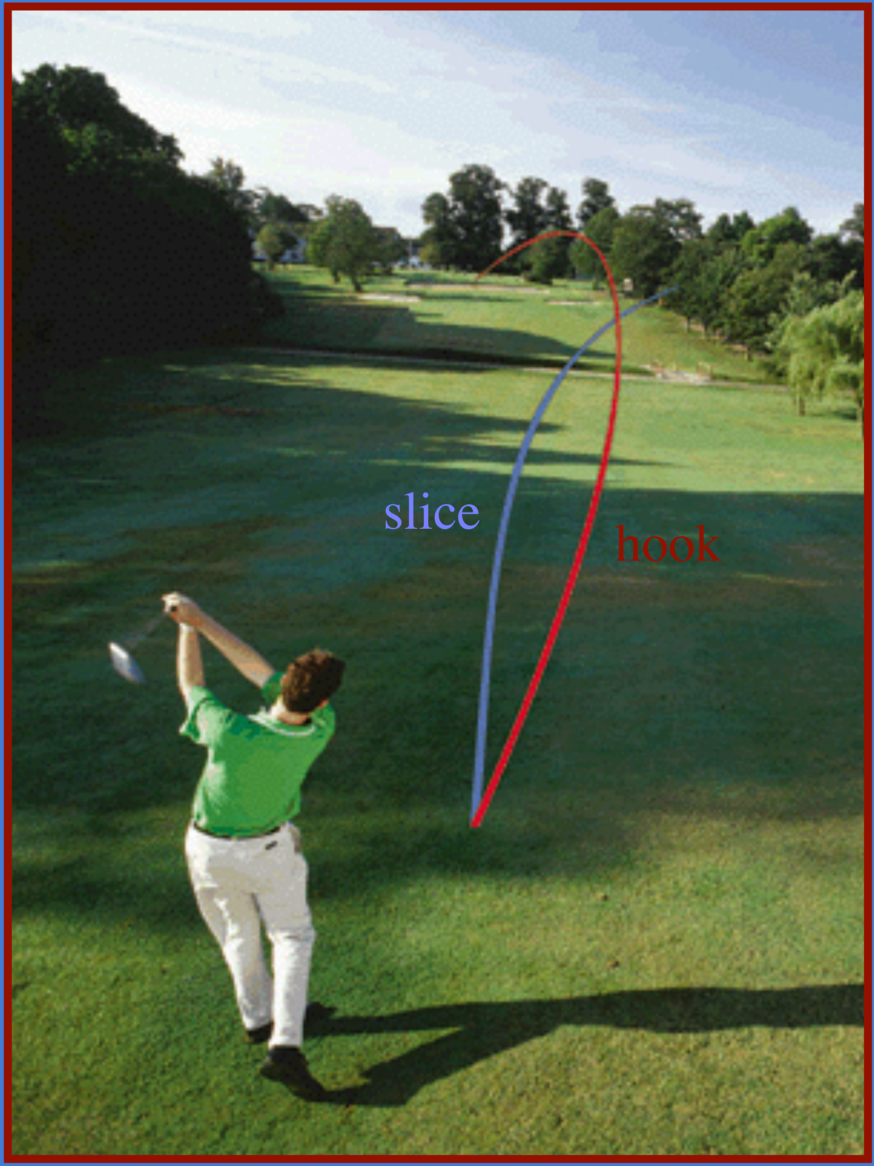


The hook

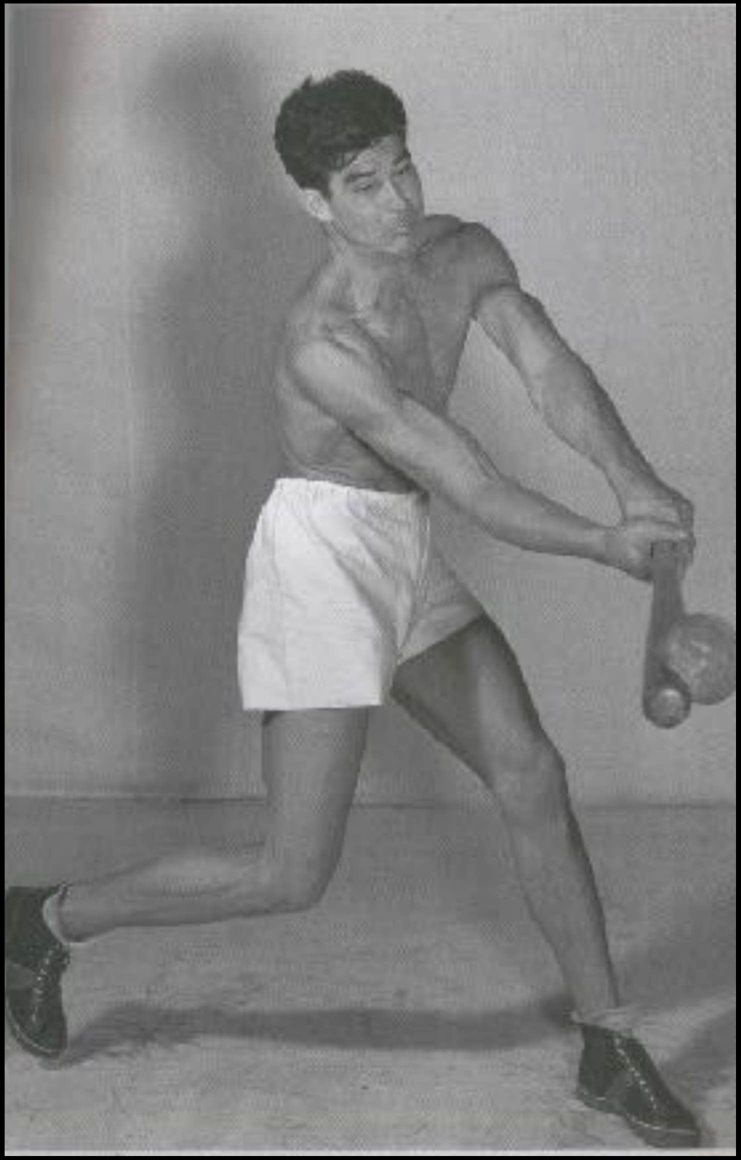


The slice





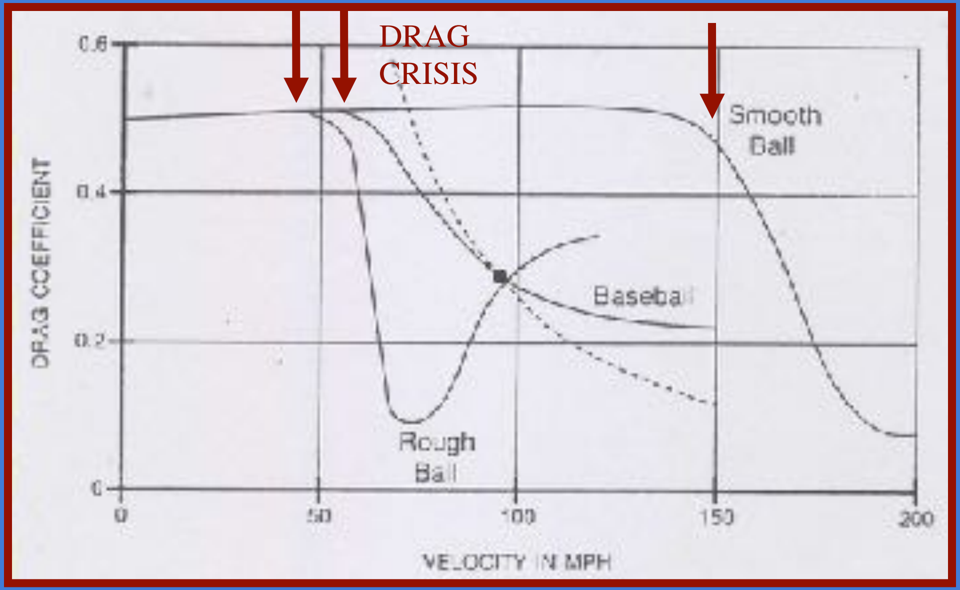
Baseball



BEFORE

AFTER

- $Re = 122{,}000 < Re_c$ (for pitching); however, turbulence introduced in the boundary layer by the seams



- Magnus effect important in trajectory of pitched and batted balls

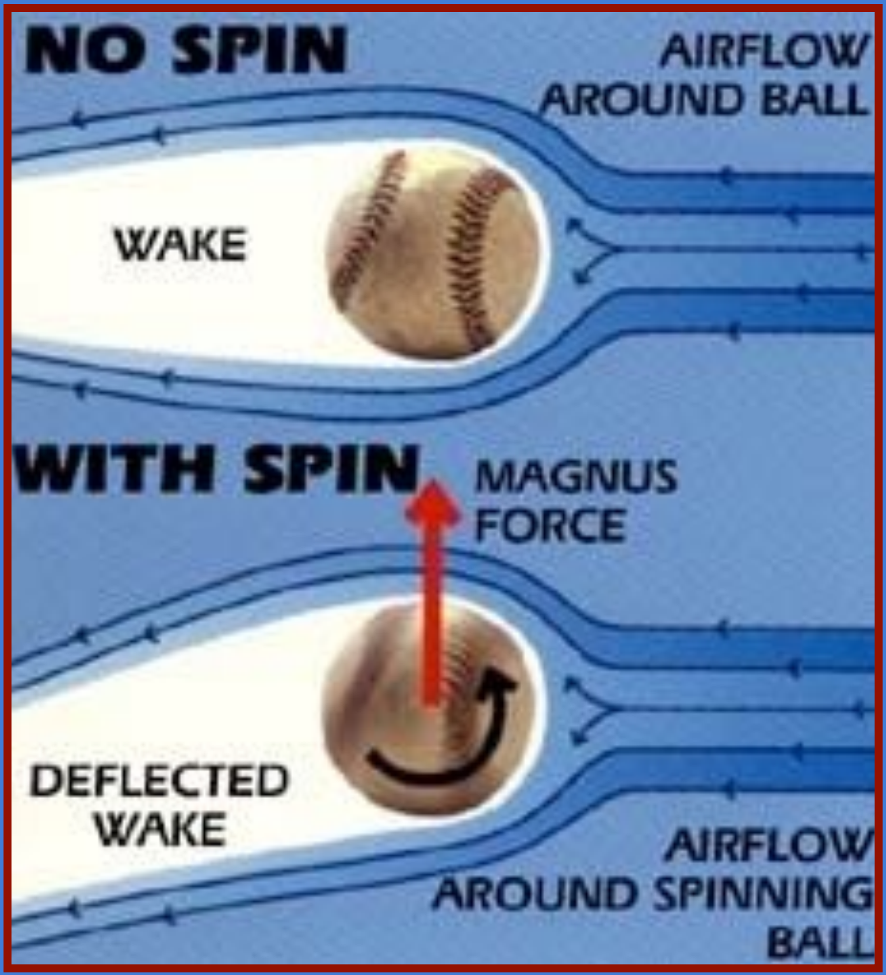
Conditions	Distance batted
With backspin of 30 rev/s	400 ft
Without backspin	380 ft
Without stitches	300 ft
In vacuum	750 ft
In Atlanta (altitude 1050 ft)	408 ft
In Denver (altitude 5300 ft)	440 ft

PITCHING

A sports writer once doubted that Dizzy Dean's curveball was anything more than an optical illusion. This provoked the great Dizzy Dean to say:

"Alright, go stand behind that tree and I'll hit you with an optical illusion".

The Magnus effect and pitching



Fastball

Curve ball

2-SEAM FASTBALL
Sidespin and backspin are generated by fingertip pressure with either the index or middle finger on the seam when the ball is released.

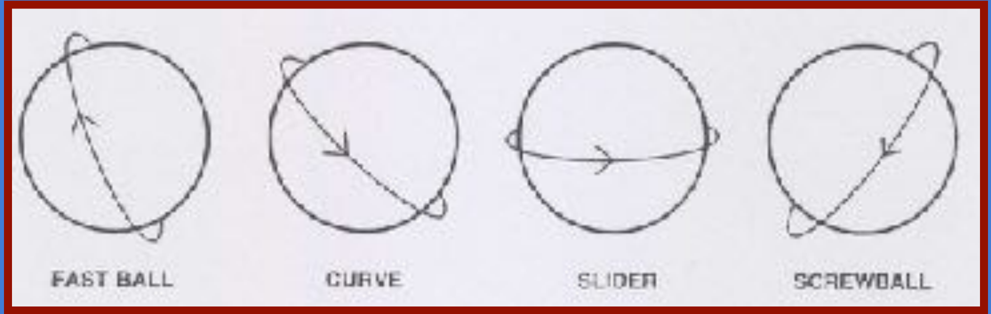
FORKBALL
Also called splitter or split-finger fastball. Ball is released with a lot of velocity but with tumbling rotation for dramatic drop at plate.

CURVEBALL
Palm is turned inward with a release like you're pulling down on the ball. Sidespin and backspin should be imparted with wrist, not elbow.

SCREWBALL
Palm is turned ou;on release and the ball breaks to the outside against righthand hitters. Velocity is slower than that of a curveball.

SLIDER
Releasing the ball off the index finger also imparts backspin and sidespin, causing lateral and downward movement.

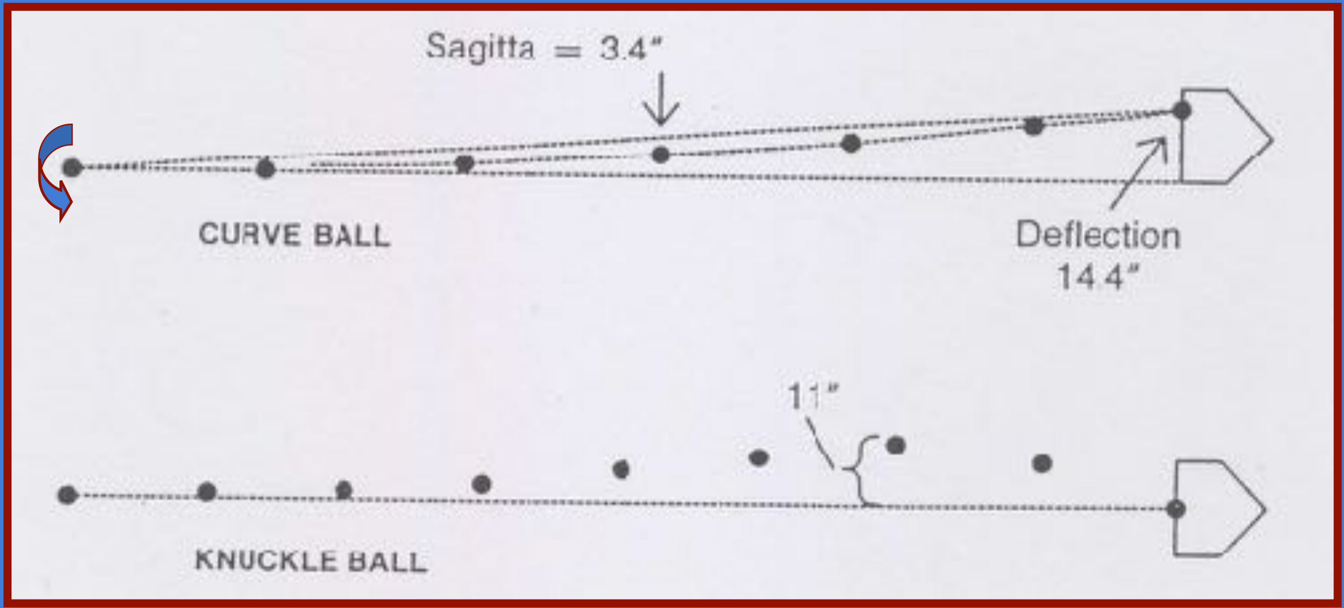
Batter's view of incoming pitches



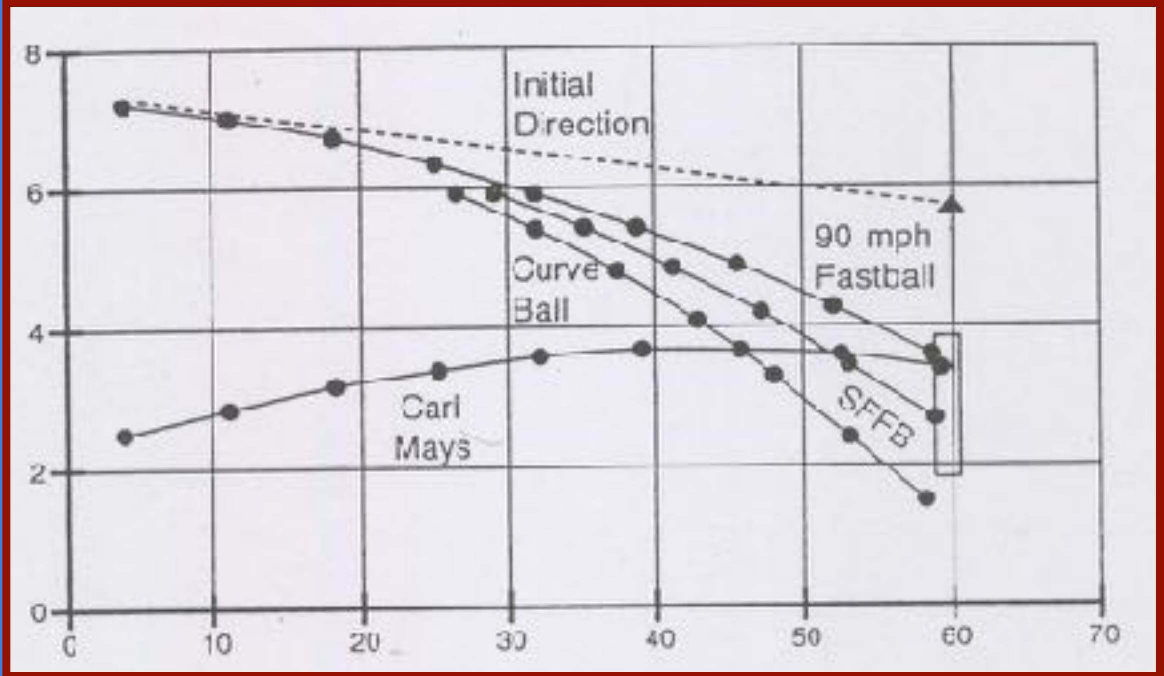
- pitcher can impart a spin of up to 25 rev/s: Magnus effect can induce deflections of about 1 ft

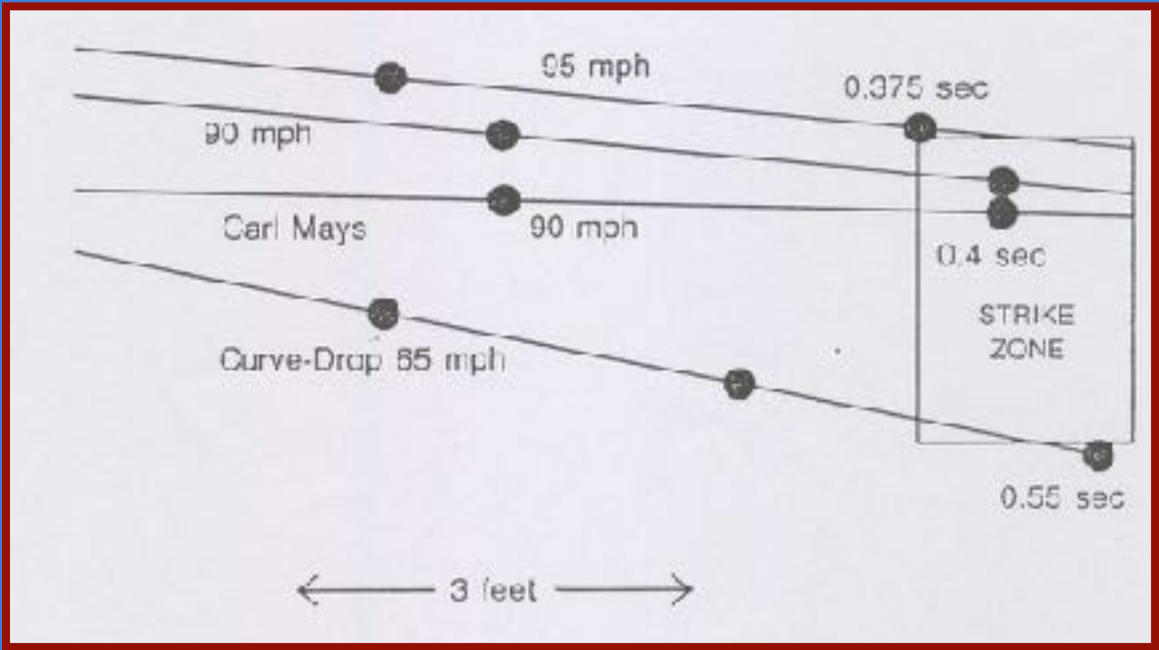
Knuckle ball: thrown `dead' (with very little spin)

- ball rotates approximately once from pitcher to plate
- trajectory determined by seam orientation
- thrown off knuckles, fingertips or with spit/vaseline



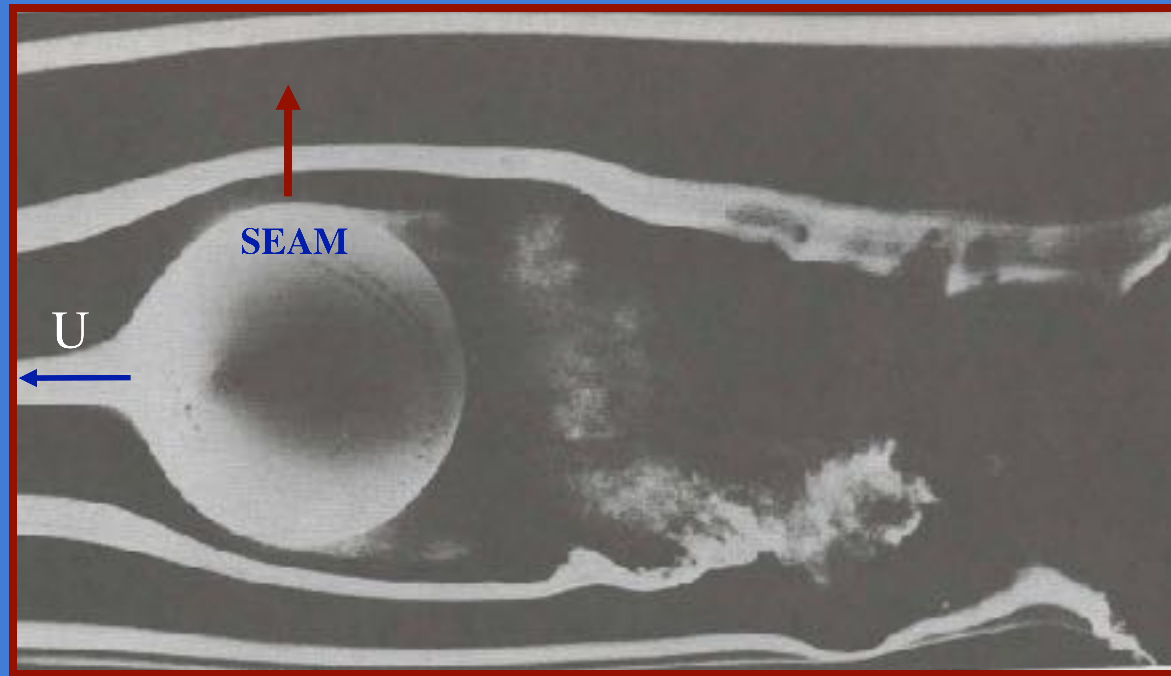
Trajectories of various pitches





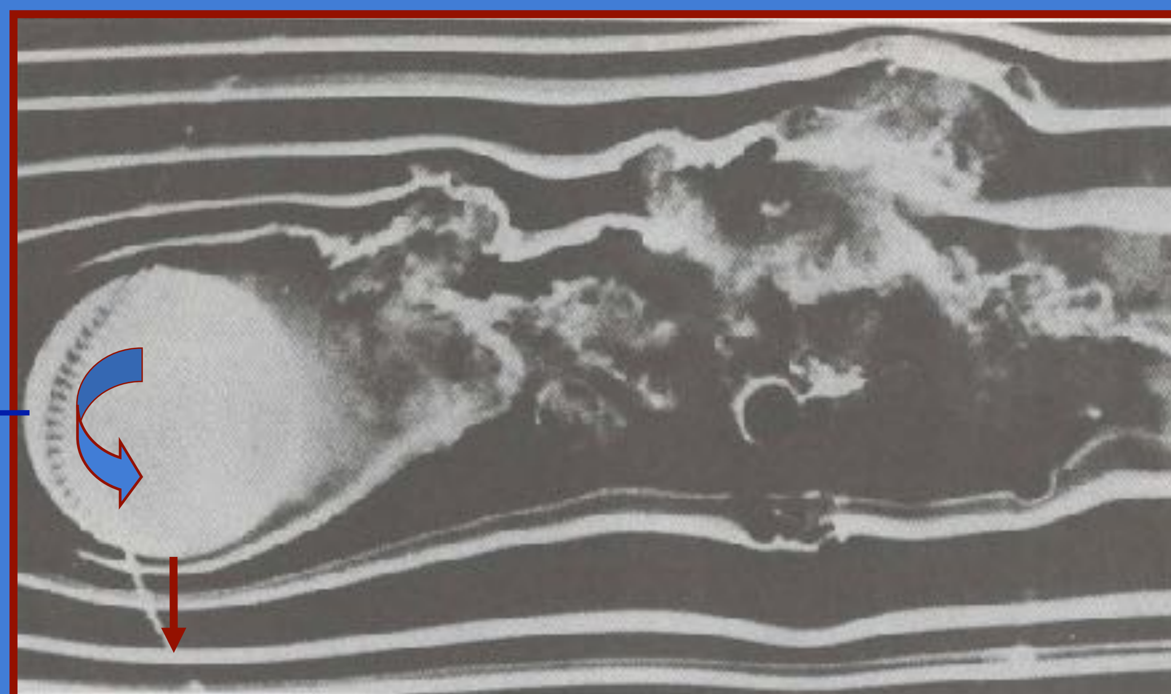
Flow past a baseball

Knuckleball



Flow past a spinning baseball

$U = 21$ m/s,
$\Omega = 15$ rev/s



U

Cricket

CRICKET

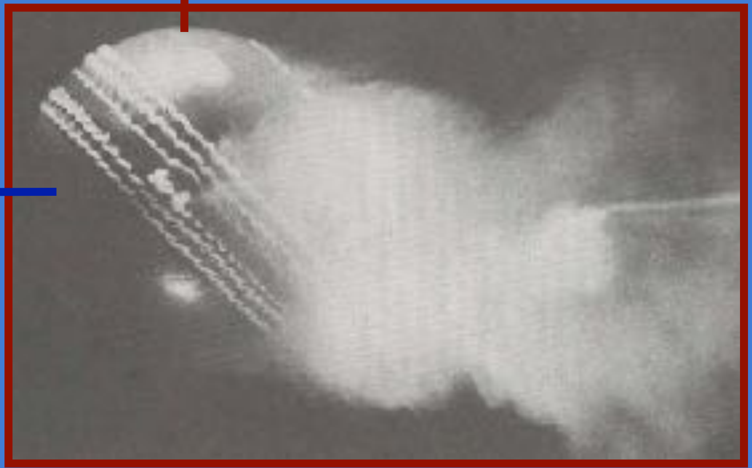
- $Re = 60{,}000 - 150{,}000 < Re_C$ (for bowling); however, turbulence is prompted in the boundary layer by the seams
- two distinct modes of bowling

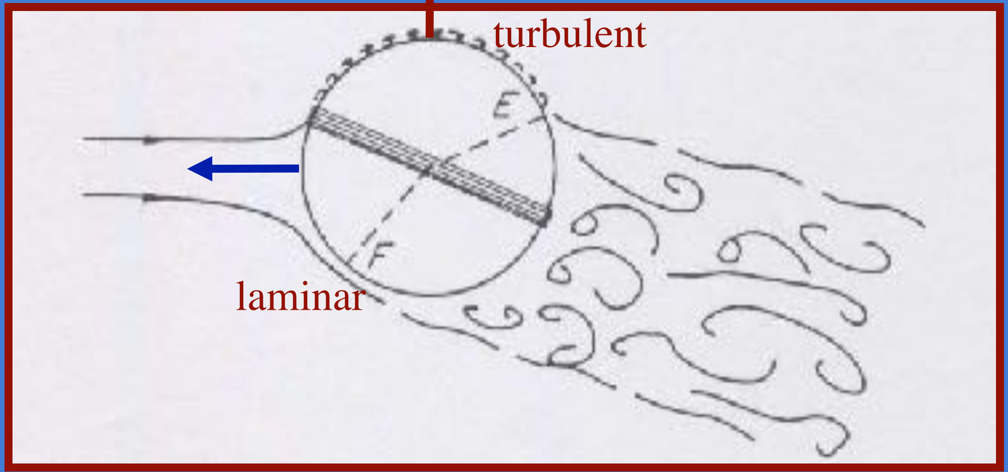
Slow (`Spin') Bowling

- typical velocity of 15 m/s
- Magnus effect generates `spin-swing'

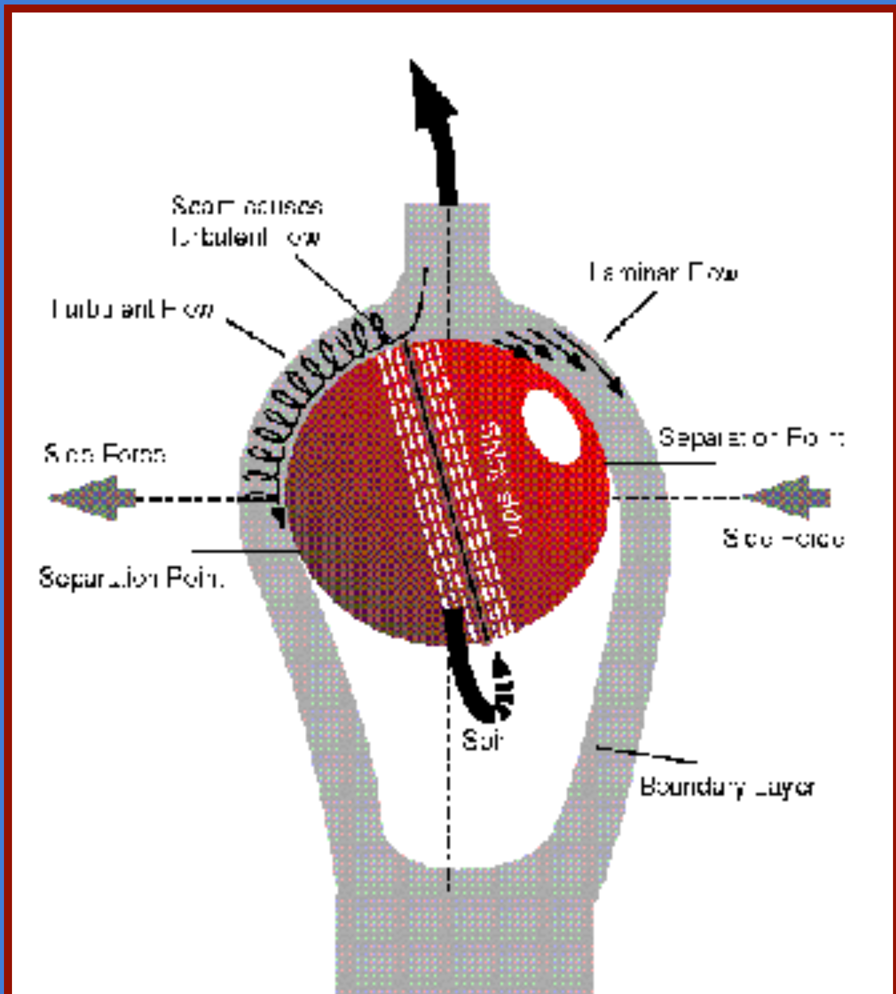
Fast (`Swing') Bowling

- seam trips turbulent boundary layer on one side: asymmetry causes swerve
- as ball wears, roughness develops on both sides: symmetry restored

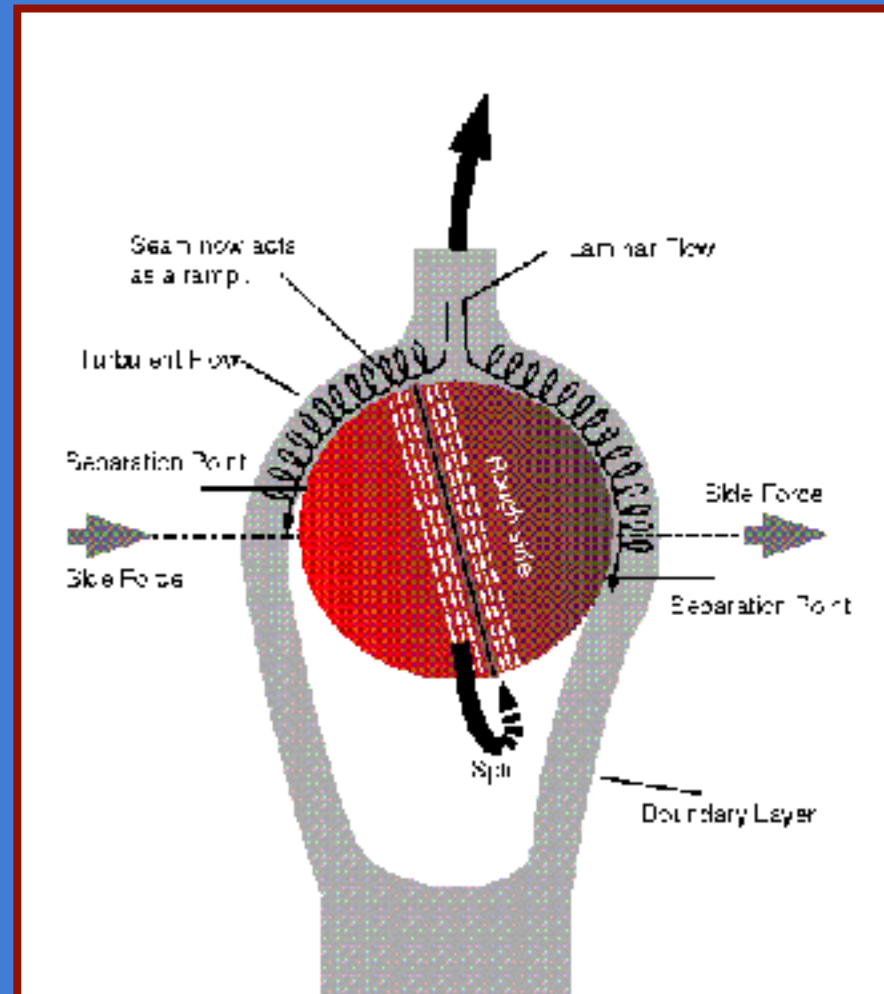




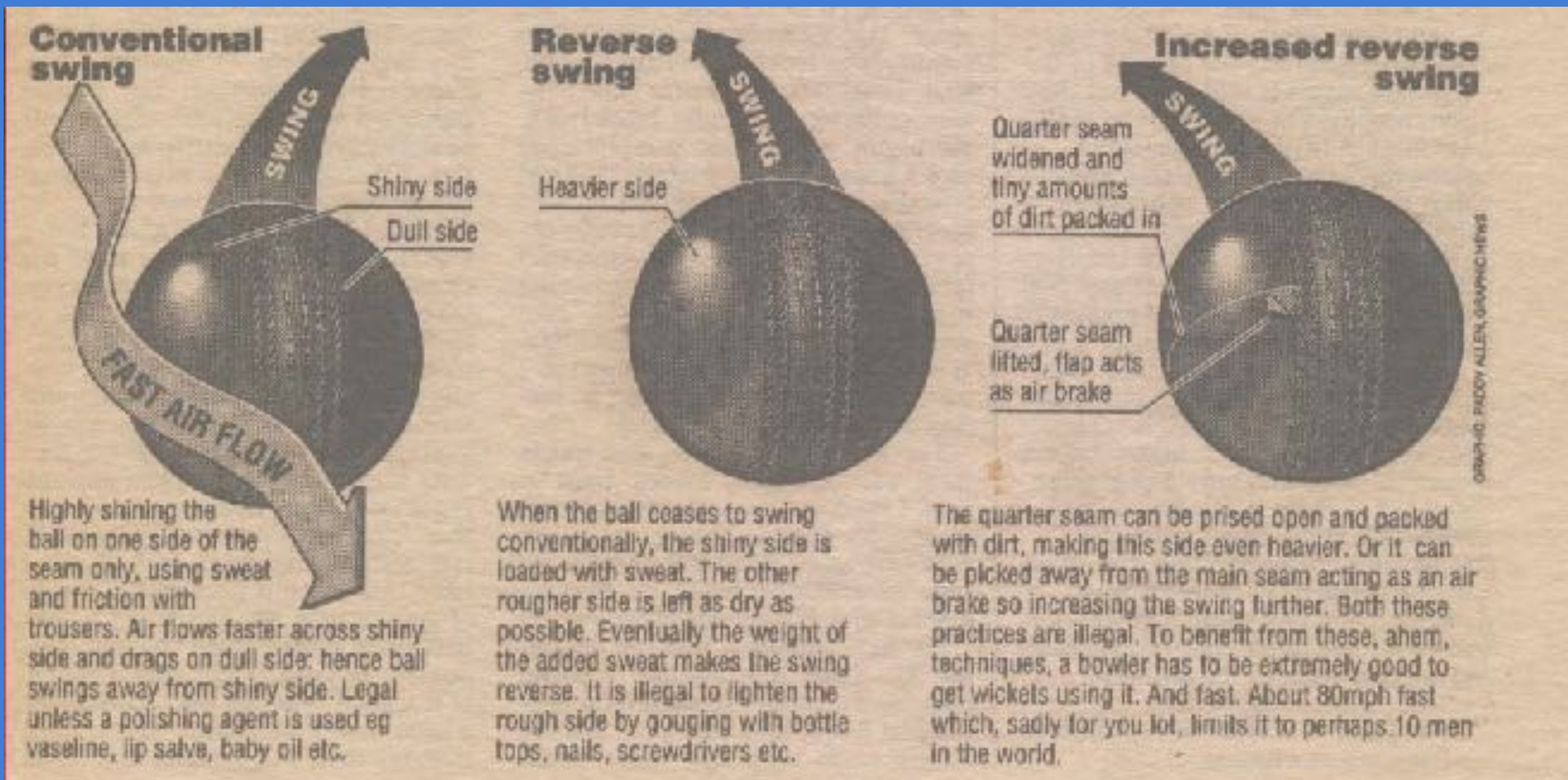
Normal swing



Reverse swing



The expert's guide to ball tampering



Highly shining the ball on one side of the seam only, using sweat and friction with trousers. Air flows faster across shiny side and drags on dull side: hence ball swings away from shiny side. Legal unless a polishing agent is used eg vaseline, lip salve, baby oil etc.

When the ball ceases to swing conventionally, the shiny side is loaded with sweat. The other rougher side is left as dry as possible. Eventually the weight of the added sweat makes the swing reverse. It is illegal to lighten the rough side by gouging with bottle tops, nails, screwdrivers etc.

The quarter seam can be prised open and packed with dirt, making this side even heavier. Or it can be picked away from the main seam acting as an air brake so increasing the swing further. Both these practices are illegal. To benefit from these, ahem, techniques, a bowler has to be extremely good to get wickets using it. And fast. About 80mph fast which, sadly for you lot, limits it to perhaps 10 men in the world.

Claim

A cricket ball swings more readily in humid conditions (on a moist day, near the sea, or when the sun goes behind a cloud!)

Proposed explanations

1. Air conditions: dependence of air density on temperature, pressure, humidity

   → NO: density of moist air less than that of dry air

2. Seam absorbs water and swells: turbulence more readily enhanced in boundary layers, decreased drag

   → refuted by wind tunnel studies (Mehta 1983)

Resolution

Sun generates a field of turbulent convection that mixes the air, and so eliminates the pressure gradient established across the ball.

(18.355 Course Project, 2004)

Conclusions

- aerodynamic drag determined by Reynolds number and surface roughness
- most ball games played in the Re range in which laminar boundary layers would obtain in the absence of surface roughness
- stitches (baseball and cricket), fuzz (tennis) and dimples (golf) play an important role in reducing drag and suppressing the reverse Magnus effect through prompting turbulence in b.l.
- air conditions (moisture, altitude) have a subtle effect on balls in flight
- anomalous curvature of balls in flight caused by the Magnus Effect, whose sense would be reversed on smooth balls

Soccer

- have adopted the Brazilian lexicon for free kicks
- have seen some cracking goals….

El mejor tiro de la historia

El mejor tiro de la historia