Airfoils, Coffee Spills, and Curve Balls

How does lift really work?

Gabriel Lombardi

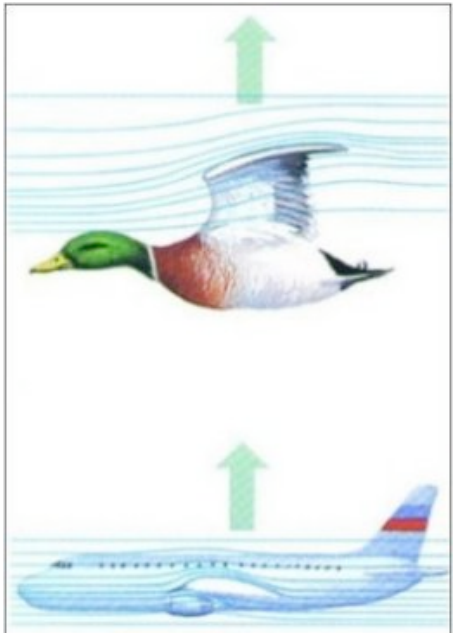


Figure 18.3 ▲
The wings of birds and airplanes both make use of the same physical principle to provide lift.

Definitions

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

$$C_L = lift \;\; coefficient$$

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

$$C_D = drag \;\; coefficient$$

$$\rho = density$$

$$v = airspeed$$

$$A = area$$

Bernoulli's Law: $$p + \frac{1}{2}\rho v^2 = const.$$

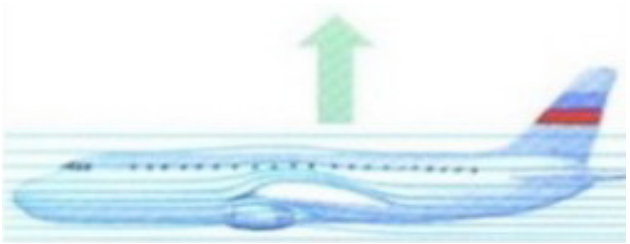
Three Explanations in decreasing BS order

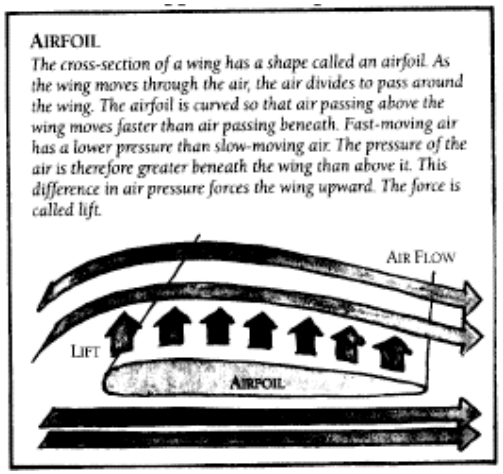
– equal times / Bernoulli
The K-8 Aeronautics Internet Textbook (lesson plans for K-6 teachers)
[http://wings.avkids.com/]
"Bernoulli's theory applied to flight: the curved upper surface of the wing forces the air to increase its speed as it flows over the top in order to reach the trailing edge of the wing at the same time as the air flowing in the path below the wing."

– Venturi / Bernoulli
Wallace Ross, **Sail Power**
"The combination of the bulge of the convex shape and the inertia of the free air stream creates a narrow channel through which the initial volume of air has to travel."

– bullets hitting the bottom, pushing off the wing

Equal times / Bernoulli



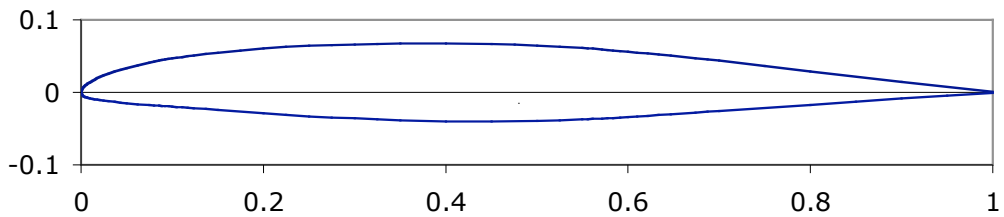


Macaulay, *The Way Things Work*

- air takes the same time to travel over the top and bottom
- top air has a longer path
- air flow is faster over the top

—> pressure is lower on top

737s can't fly!



737 airfoil, outboard (1.25%)

location	Δv/v
root	0.23%
midspan	0.97%
midspan	1.16%
outboard	1.25%

$$p + \frac{1}{2}\rho v^2 = const.$$

$$\Delta p = -\rho v^2 \frac{\Delta v}{v}$$

$$F_L = |\Delta p| A = \rho v^2 \frac{\Delta v}{v} A$$

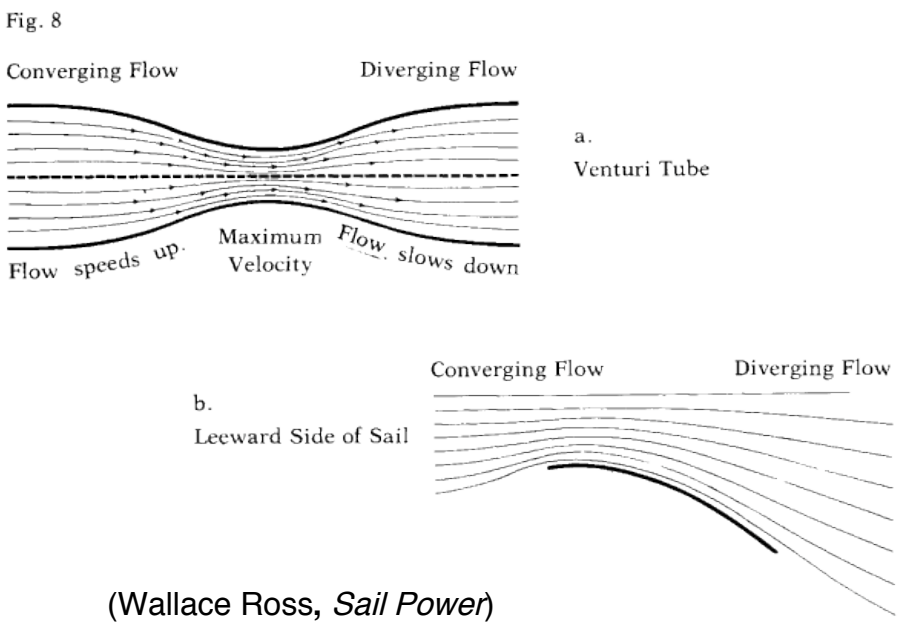
$$C_L = 2\frac{\Delta v}{v}$$

cruising altitude	35,000	ft
air density	0.38	kg/m^3
airspeed	220	m/s
wing area	100	m^2
takeoff mass	60,000	kg

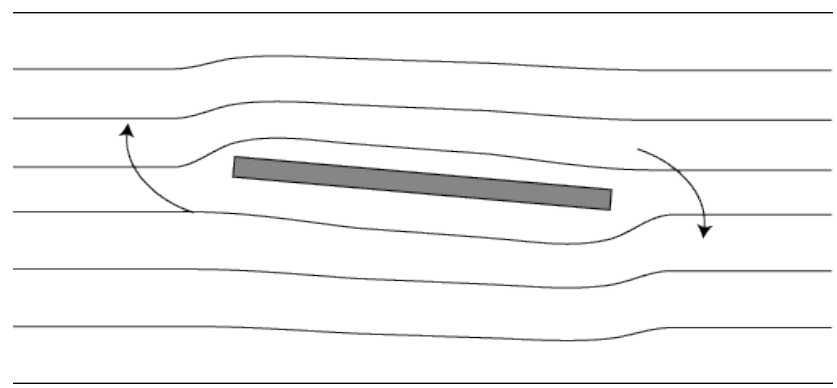
lift	22,990	newton
weight	588,000	newton

Venturi / Bernoulli

(“Flat plates have no lift.”)



(Wallace Ross, *Sail Power*)



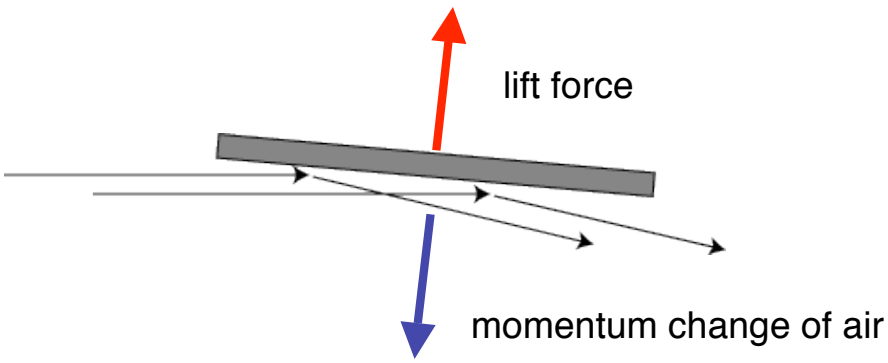
torque, but no lift

"Given the proper power and inclined at the right angle, a barn door could be made to fly."
– Wilbur Wright

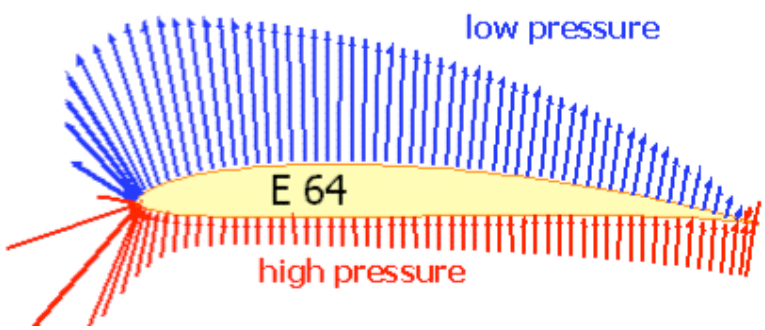
lift coeff. of a flat plate $C_L = 2 \pi \alpha$
(Landau, L. D. and Lifschitz, E. M. Fluid Mechanics, 2nd ed.)

Bullets bouncing off the bottom

("Airfoils never stall.")



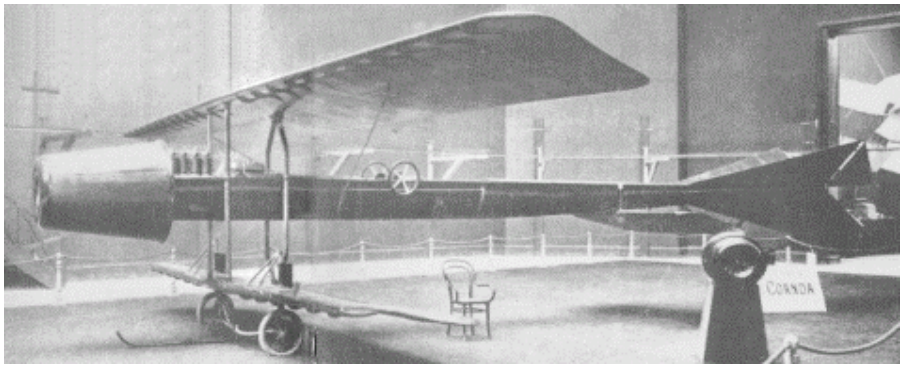
$$F = \frac{dp}{dt} = \frac{dm}{dt}\Delta v$$



Why bother about the shape of the top?

Most of the lift is from the top!

Coanda Effect

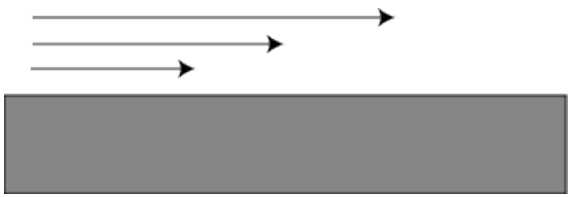


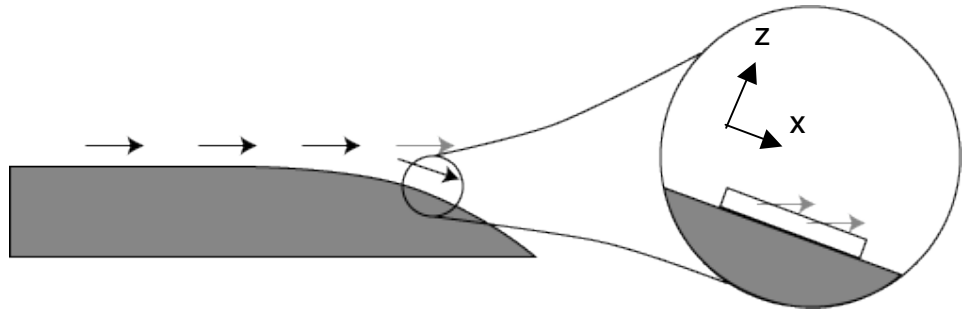
Henri Coanda's jet-propelled airplane (1910)

Exhaust from the engine hugged the fuselage.

Fluids tend to stick to surfaces (flow attachment).

Coanda Effect, contin.





continuity:

$$\nabla \bullet v = 0$$

$$\frac{\partial v_x}{\partial x} + \frac{\partial v_z}{\partial z} = 0$$

boundary conditions:

$$v_x(x,0) = 0$$

$$v_z(x,0) = 0$$

$$\Rightarrow \frac{\partial v_z}{\partial z} = 0$$

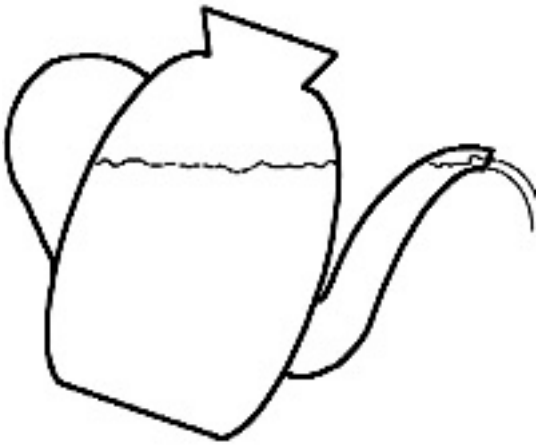
Viscosity causes shear.

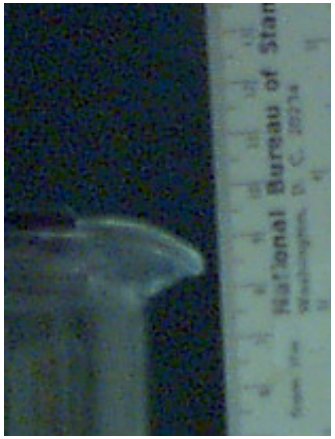
Shear causes attachment.

Viscosity sets the v_x boundary condition.

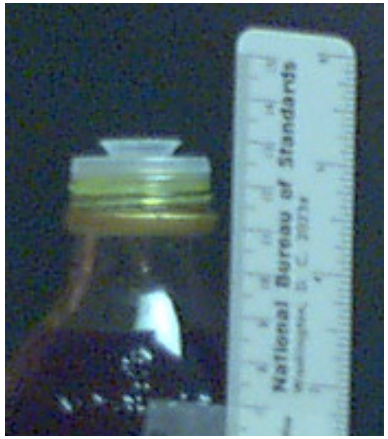
Continuity makes the flow parallel to the surface

Drippy spouts





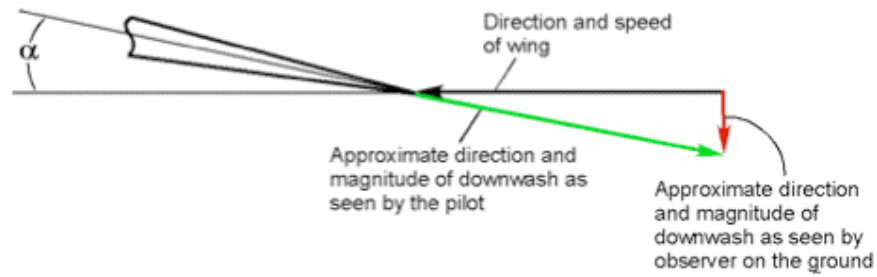
drippy



not drippy

Sharp spouts don’t drip because the flow detaches.

Downwash



http://www.aa.washington.edu/faculty/eberhardt/lift.htm

$$F = \frac{dp}{dt} = \frac{dm}{dt}\Delta v$$

In the reference frame of the ground, downwash is straight down.

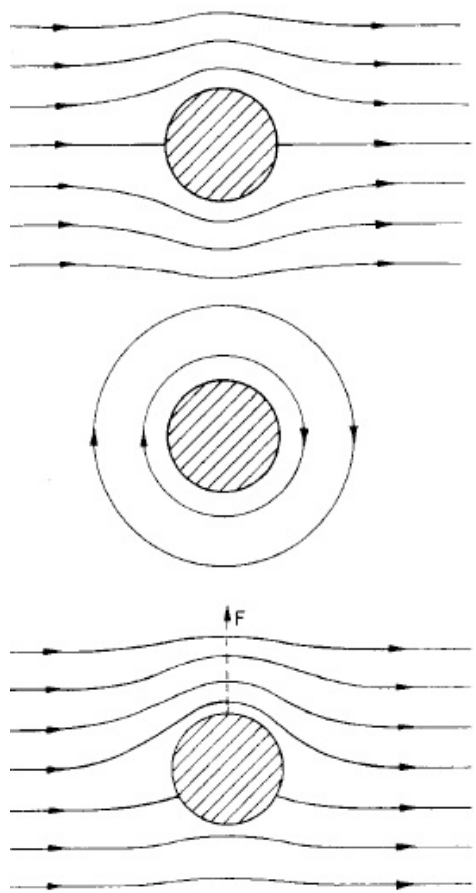
Helicopters and fans

Magnus effect

flow past a cylinder

add circulation

lift

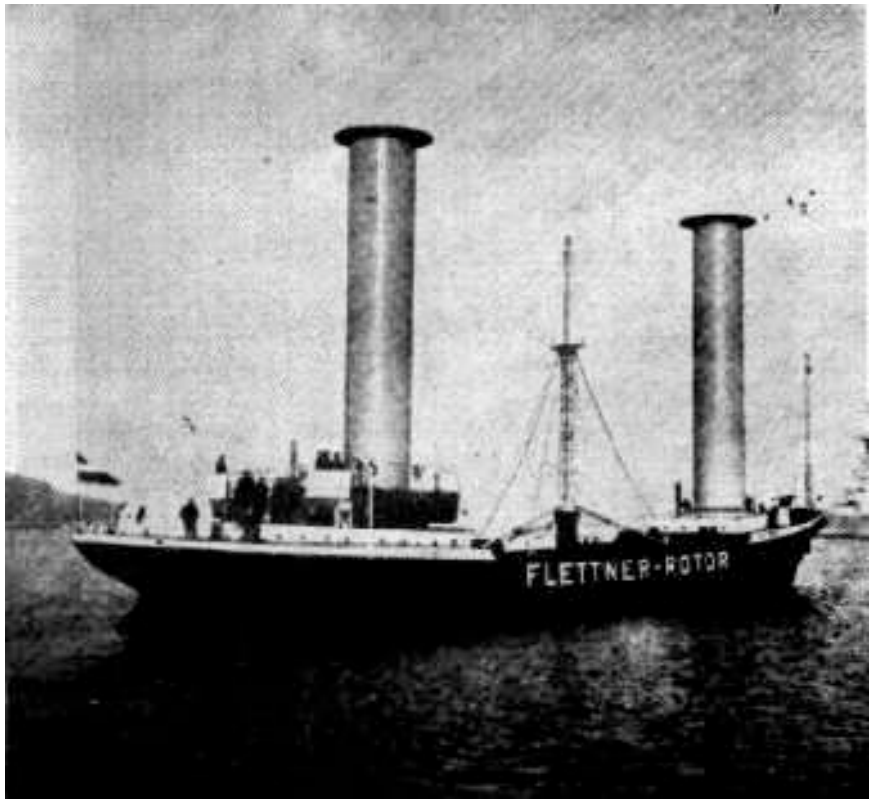


Feynman Lectures, vol. 2

Flow plus circulation makes lift.

A spinning ball causes circulation *if* there is viscosity.

Flettner's Ship



– rotating cylinders in the wind cause lift
– trans-Atlantic voyage: 1926

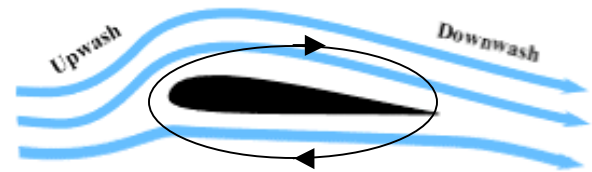
Kutta-Zhukovski Theorem

$$F_L = \rho \Gamma v L$$

$$\Gamma = \oint v \;\; dl$$

$$\approx (v_u - v_l) W$$

$$\Rightarrow F_L = \rho (v_u - v_l) v L W$$



$$P_u - P_l = \frac{1}{2}\rho\left(v_l^{\,2} - v_u^{\,2}\right)$$

$$= \rho (v_l - v_u)\frac{1}{2}(v_l + v_u)$$

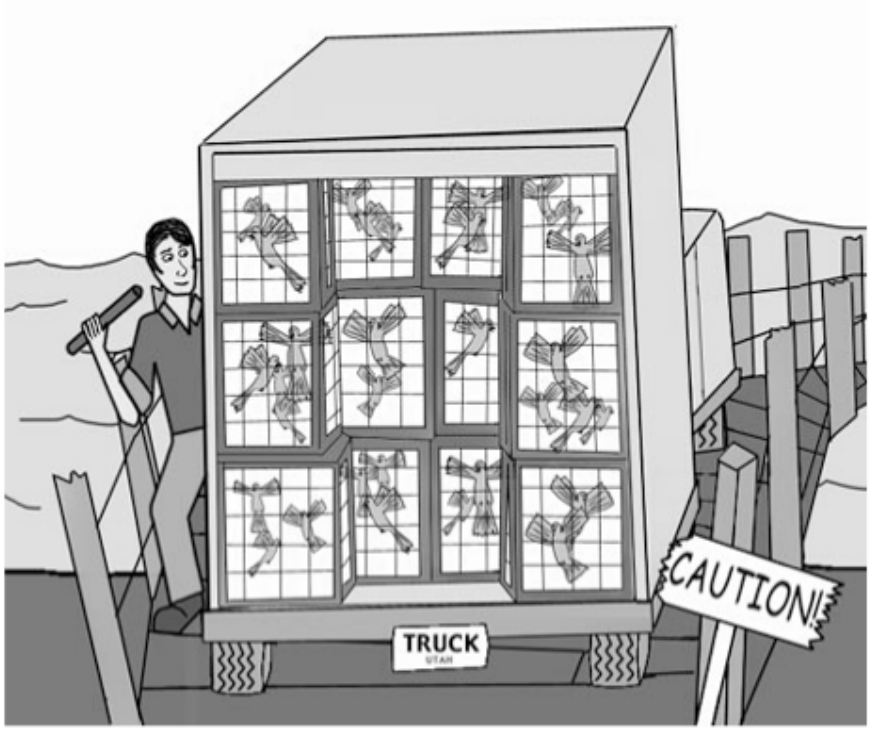
$$\approx \rho (v_l - v_u) v$$

$$F_L = (P_u - P_l) L W$$

$$= \rho (v_l - v_u) v L W$$

viscosity —> circulation (vorticity) —> lift

Canaries in a truck



2 tons of canaries
2 ton truck
3 ton capacity bridge