The Abdus Salam
International Centre for Theoretical Physics

United Nations
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2234-20

Meeting of Modern Science and School Physics: College for School Teachers of Physics in ICTP

27 April - 3 May, 2011

Physics of Sailing

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Symmetry in the world of water and air : a comparison of forces in the physics of sailing

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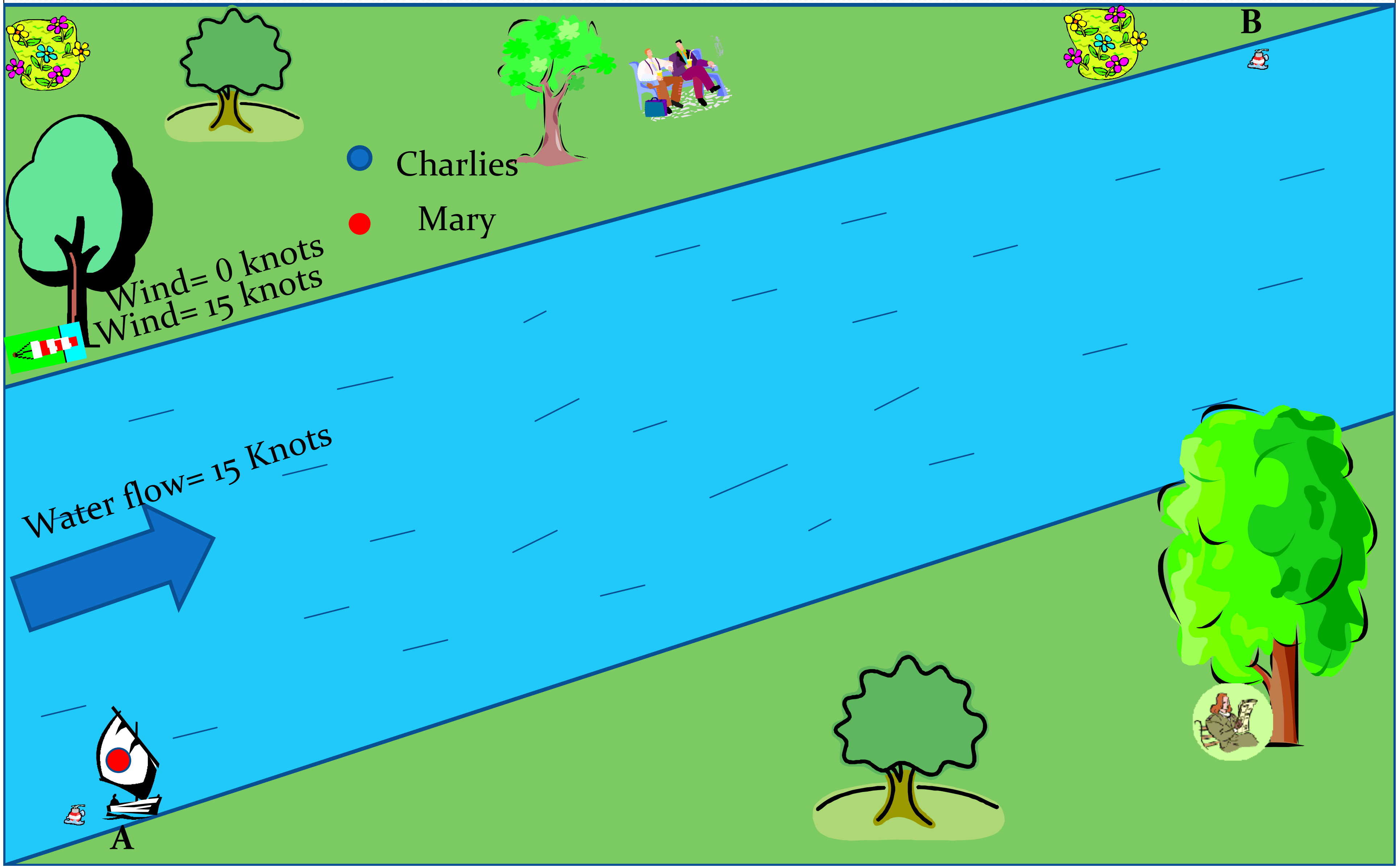
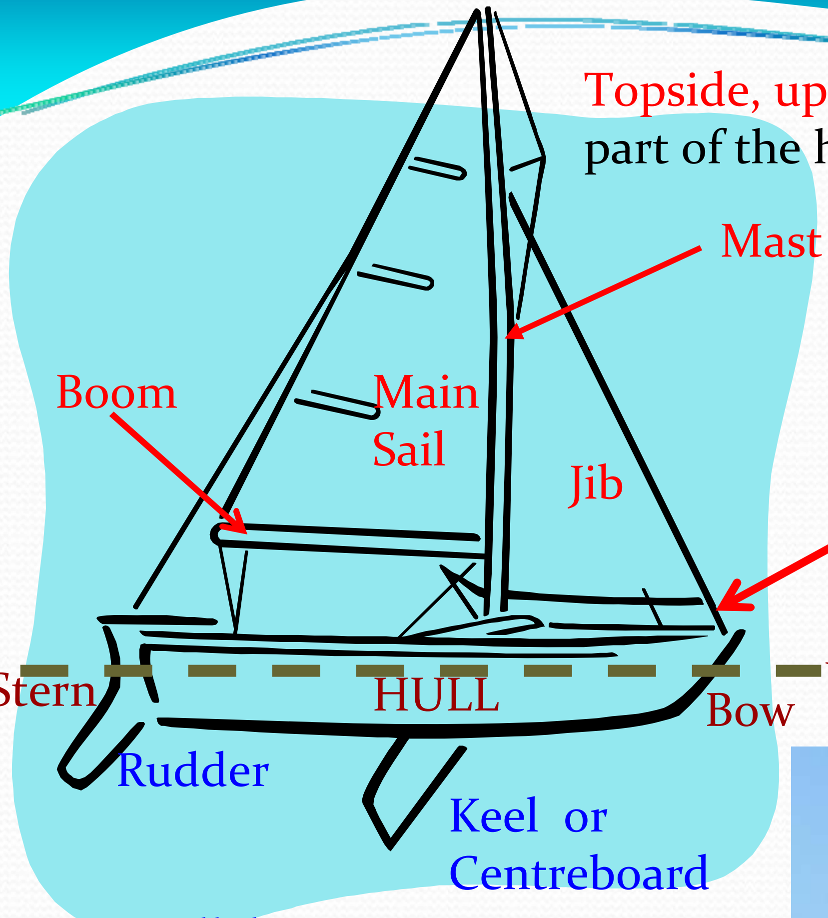
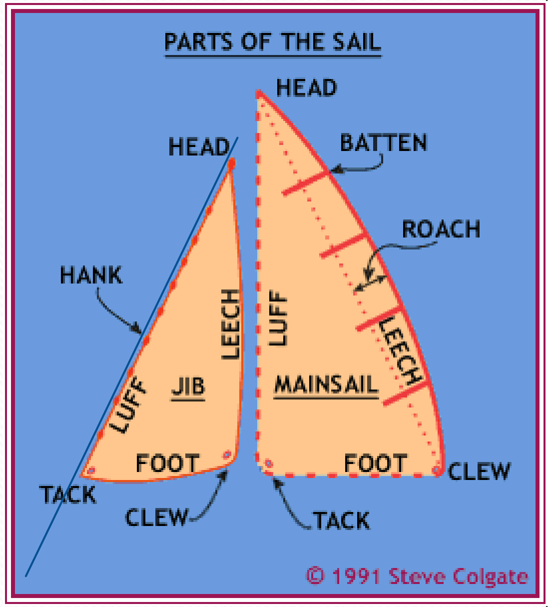
Quiz


B
Charlies
Mary
Wind= 0 knots
Wind= 15 knots
Water flow= 15 Knots
A

Topside, upper work:
part of the hull emerging from



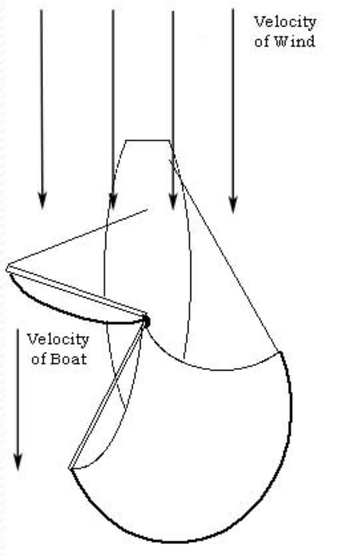
Hull, bottom:
submerged part



Air enters at the luff
and exits at the leech

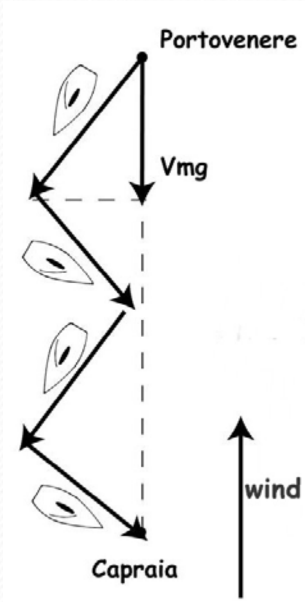
spinnaker

Sailing point

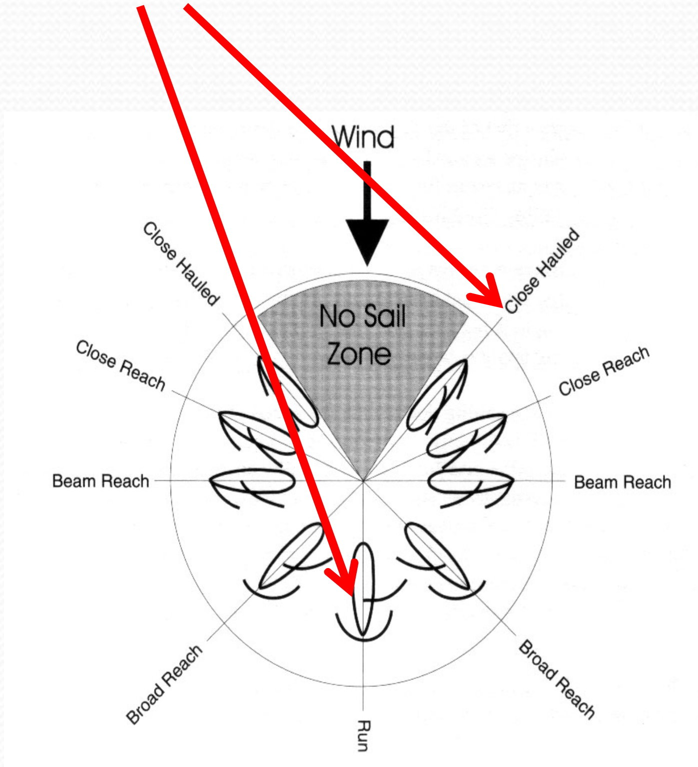


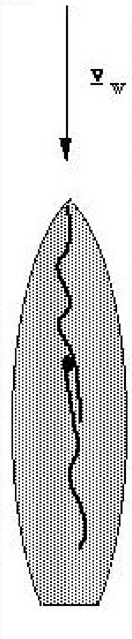
Sailing downwind (parallel to the wind,) is easy to understand: the wind pushes on the sail completely

Sailing upwind



The role of the sail
is completely different





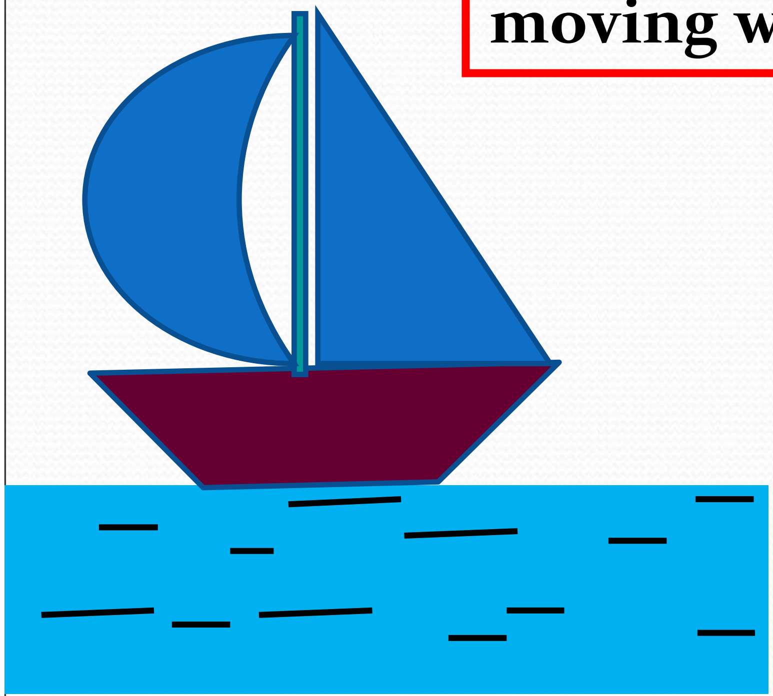
Sailing *directly* upwind (exactly anti-parallel to the wind, like the boat at right) is also easy to understand: it's impossible.

Sails flap like flags in the wind

But boats can sail at say 40° to the wind and, by tacking (alternate lines on either side of the wind direction) they can go where they like.

What is a sailboat?

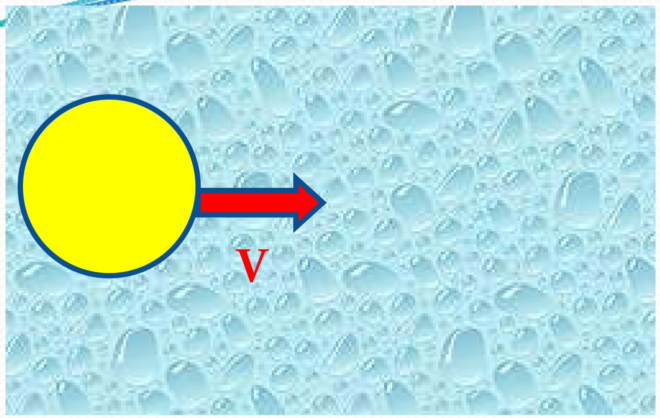
The boat is a system submerged in two fluids moving with respect the mainland.



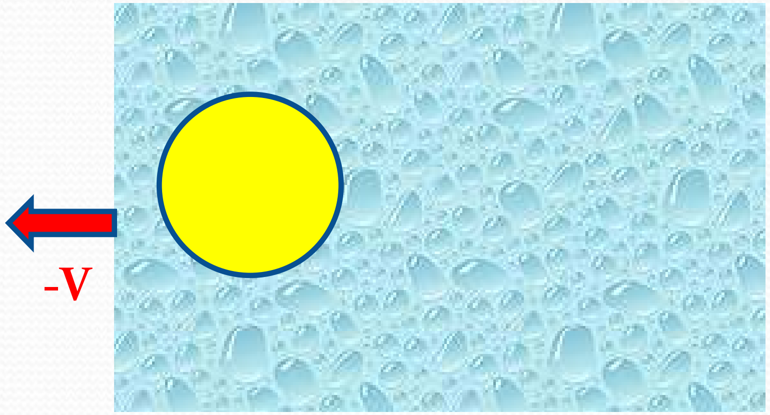
air ⇨ wind   water ⇨ current

and more...

To steer the boat is necessary that the two fluids
have a different speed and they are in relative motion.



An object moves in a fluid



A fluid moves around an object

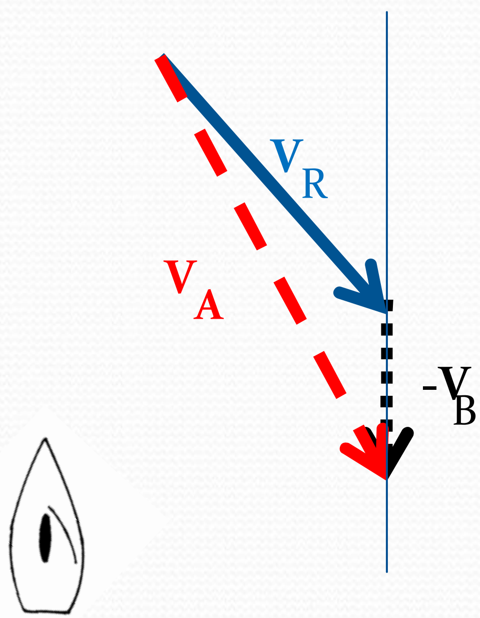
THE DYNAMIC IS THE SAME

True wind and apparent wind

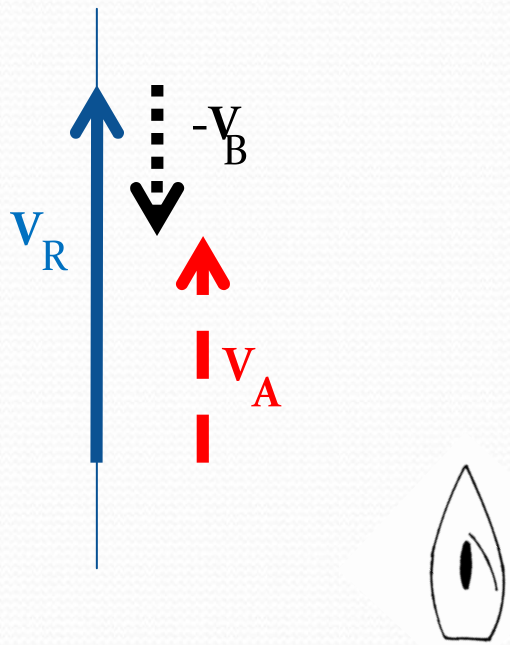
During the navigation we think to be still in a world that moves around us.

We feel an **apparent wind** that comes from one direction different from that in which the **real wind** blows

$$V_A = V_R - V_B$$



Upwind



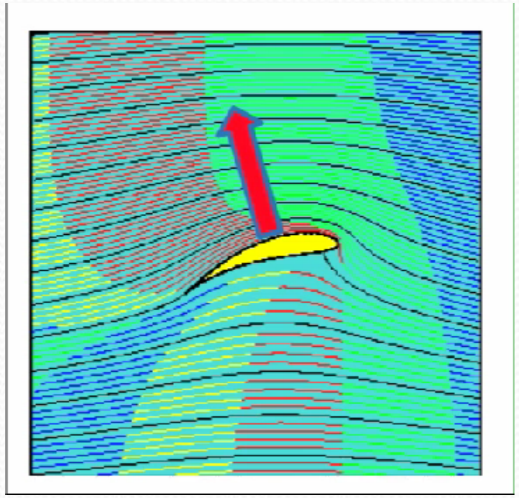
Downwind

a fluid in motion around a body

exerts a **force:**

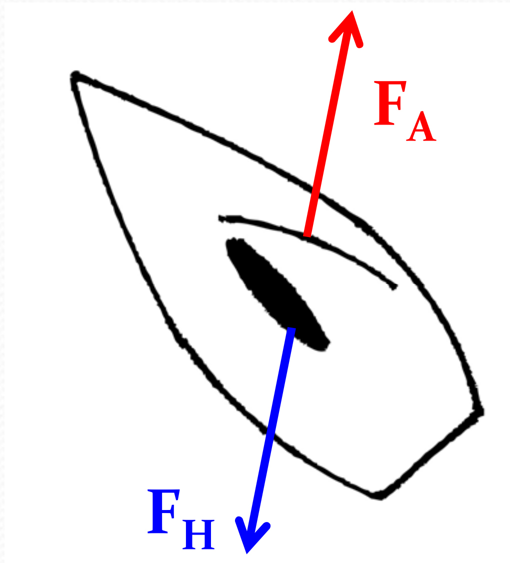
2 fluids ➡ 2 forces { aerodynamic on sails / hydrodynamic on hull

- aerodynamic
  - on sails
- hydrodynamic
  - on hull



To sail at a constant speed:

$$F_A = -F_H$$

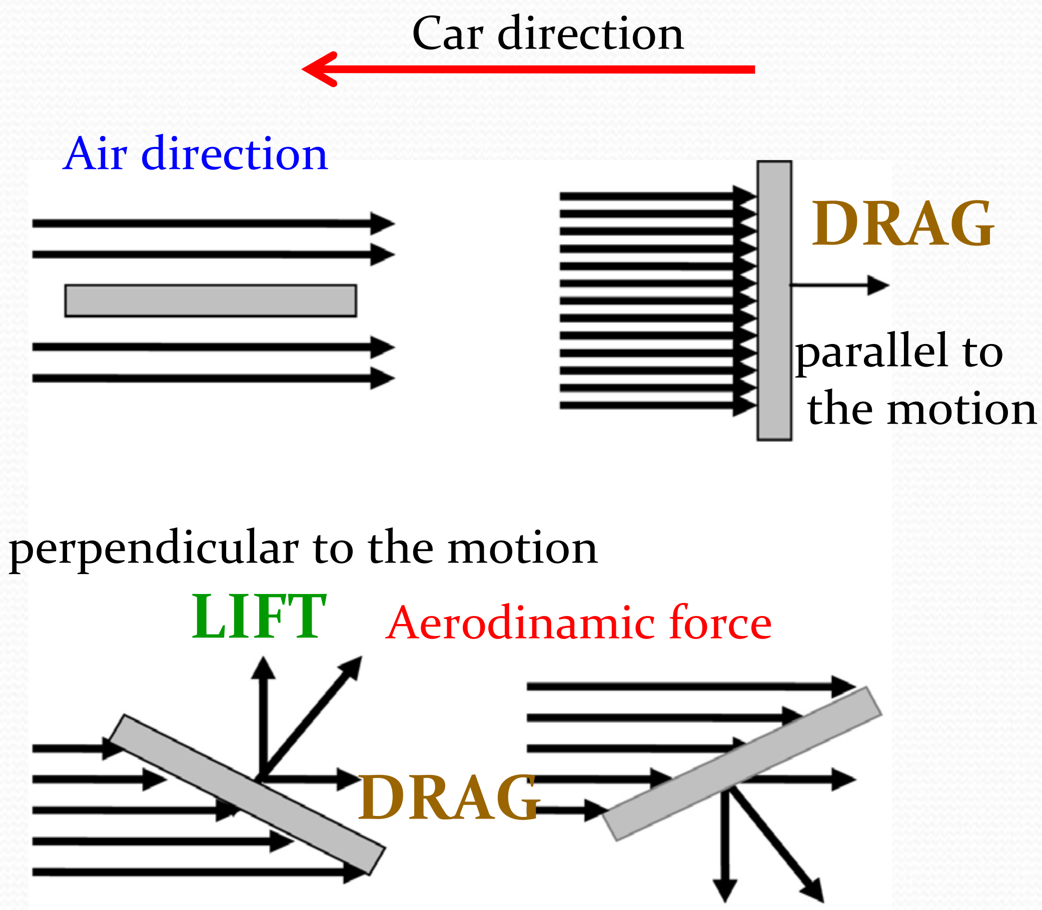


LIFT + DRAG = FORCE

What is the origin of the two forces ?

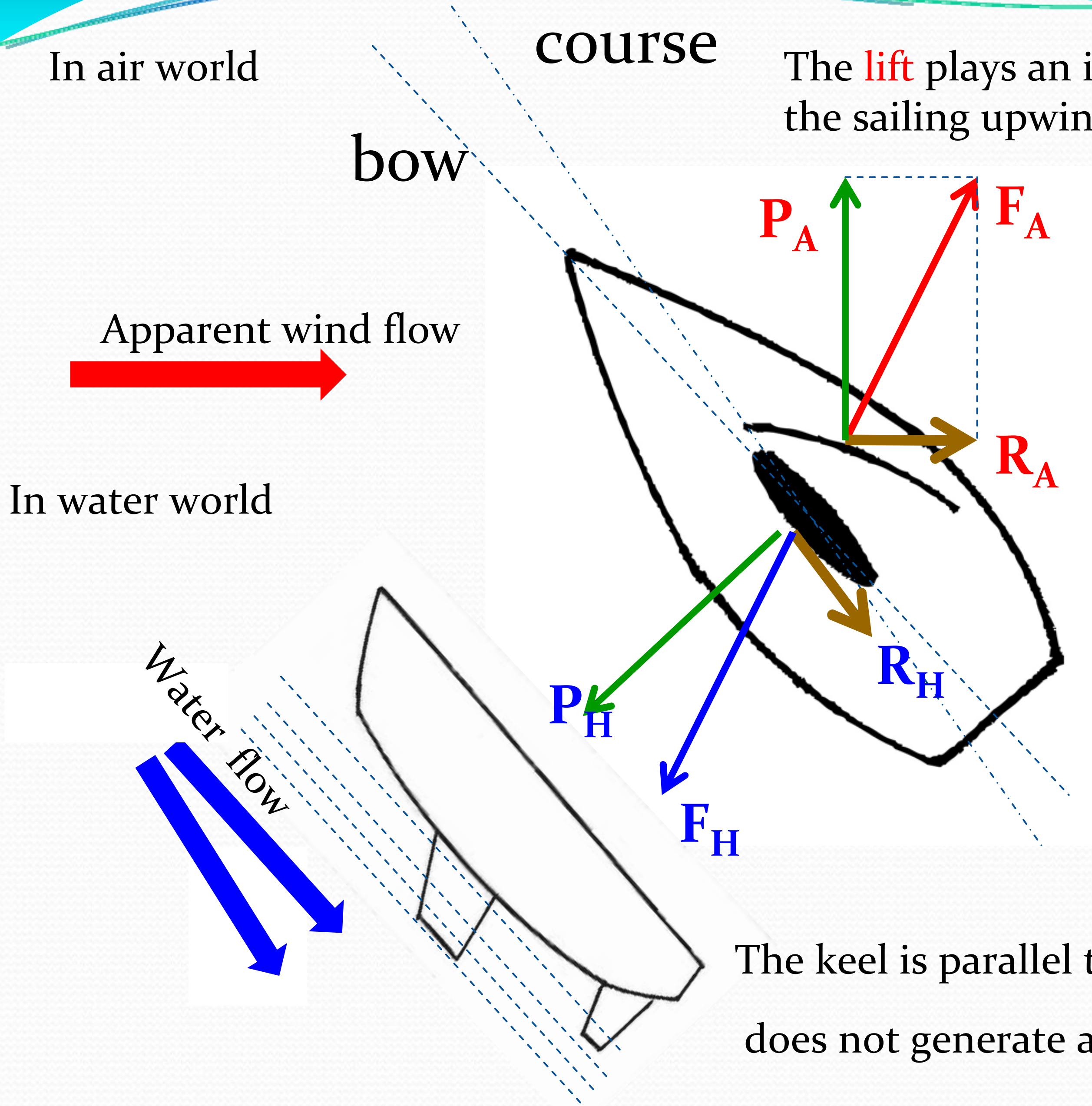
What is their direction?

They depend on
- the physical characteristic of the fluids
- the body shape
- the orientation of the body with respect to fluid flow

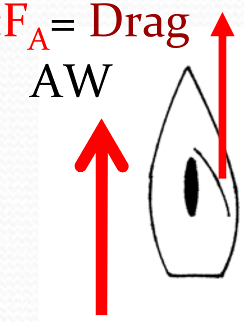


little experiment

The lift plays an important role in the sailing upwind



Downwind : F_A = Drag



It is said that the boat is making leeway

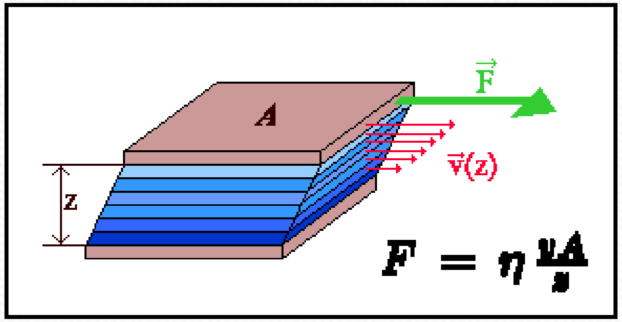
Symmetry axis

The keel is parallel to the water flow

does not generate any force

Fluids

Fluid from the Latin *fluére* (flow) is a substance that continually deforms (flows) under an applied shear stress, no matter how small. (liquids, gases)



The effect is due to internal friction forces resisting creep

η_{air}=1.5×10^{-5}Nsec/m^2 $\eta_{gas} << \eta_{liq}$ η_{water}=1×10^{-3}Nsec/m^2

ρ_{air}=1 kg/m^3 ρ_{water}=1000kg/m^3

Physical characteristics :

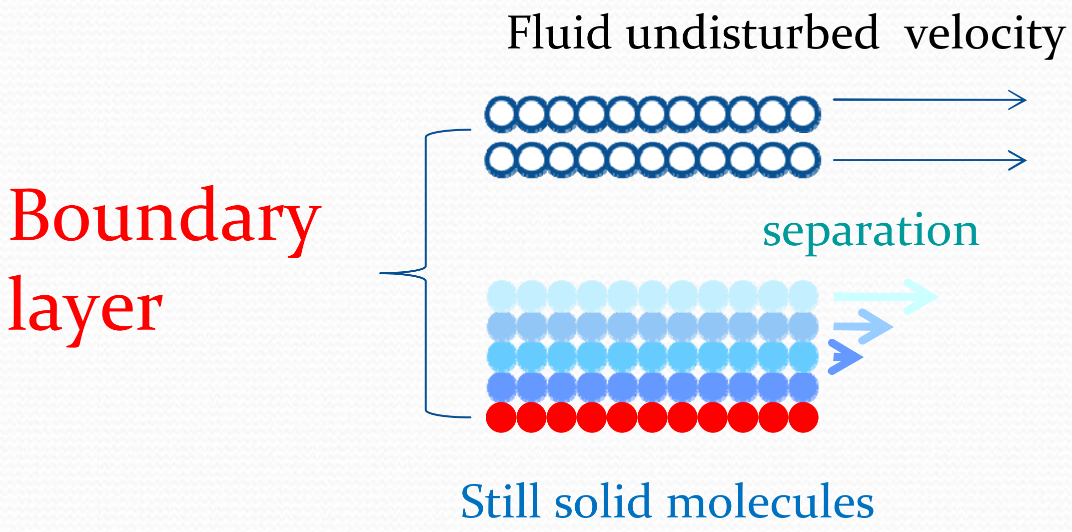
Dynamic Viscosity : η

Density : ρ=mass/volume

Kinematic Viscosity : $\nu=\eta/\rho$

Ratio between the forces due to the friction and those due to the gravity

Boundary layer



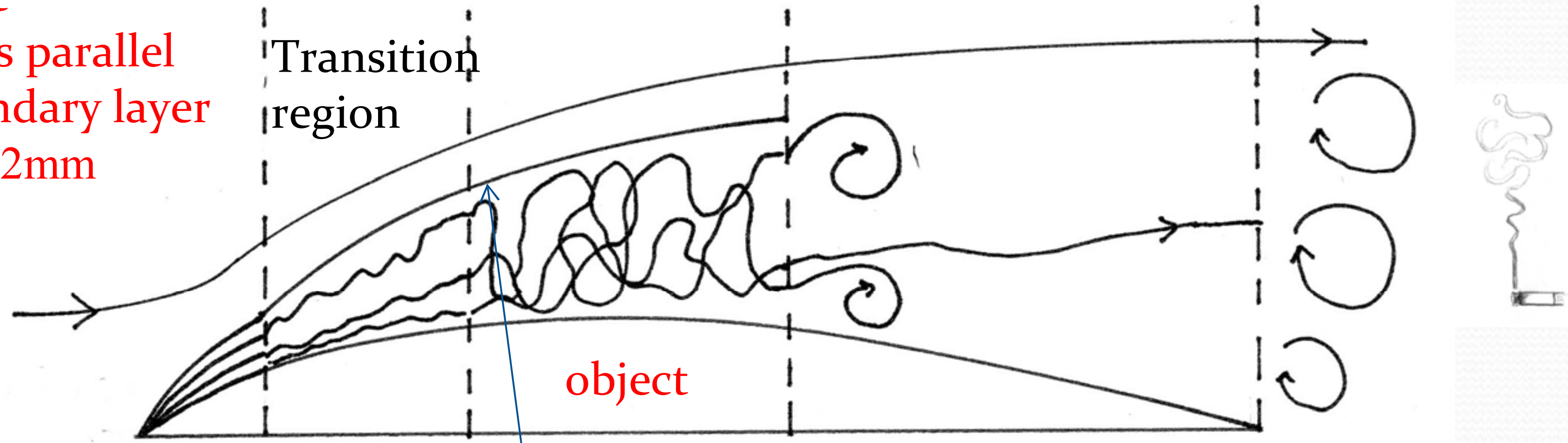
Boundary layer

Turbolent:
- Disordered motion with vortices
- Boundary layer tickness ≈12mm

Laminar:
- small zone
- Fluid layers parallel
- Small Boundary layer tickness ≈2mm

separation

wake



Undisturbed stream
$v = v_{mainstream}$

Leading edge

Limit of the boundary layer :
between v=0 and $v = 90\%\ v_{mainstream}$.
The tickness increases as you move from the leading edge

Laminar and turbolent motion

No available the movie

Low velocity ➡ Laminar motion

High velocity ➡ Turbolent motion

The fluid, moving around the object, is subject to two competitive effects

Viscous forces :

move the layers parallel to each other → η

Laminar motion

Inertial forces:

move the layers one on top → ρ

Turbolent motion

REYNOLD NUMBER

$$R_e = LV\frac{\rho}{\eta}$$

L → Distance from the leading edge

The transition between laminar and turbolent motion occurs for Re≈500000 ÷1000000

V_{boat}=5 knot=2.6m/sec (1knot=1.852 Km/h) the laminar region length

on the hull L=1000000×0.001/(1020×2.6)m=38cm

on the sail L=1000000×0.000015/(1×2.6)m≈6 cm

DRAG

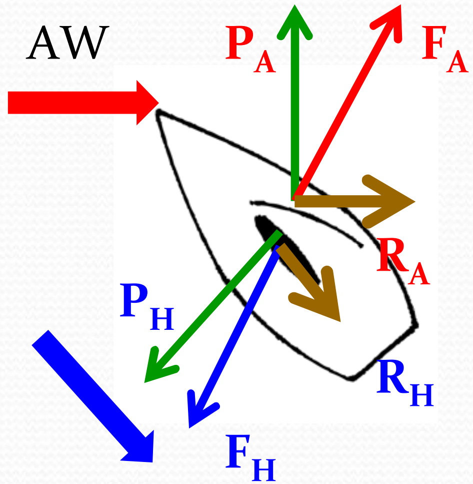
Or the price to pay in order to move

The drag is formed in the boundary layer due to the viscosity of the fluid

HULL

Hydrodynamic drag

component of hydrodynamic force
parallel to the water flow



SAILS

Aerodynamic drag

component of aerodynamic force parallel to the apparent wind

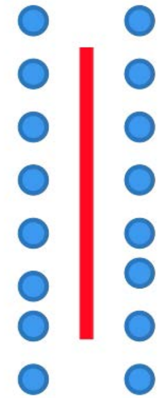
In all cases it is opposite to the motion, except the aerodynamic drag when we are sailing downwind

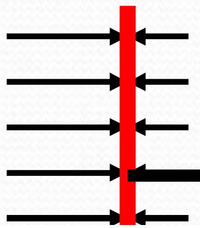
Total drag

- Friction drag
- Pressure drag

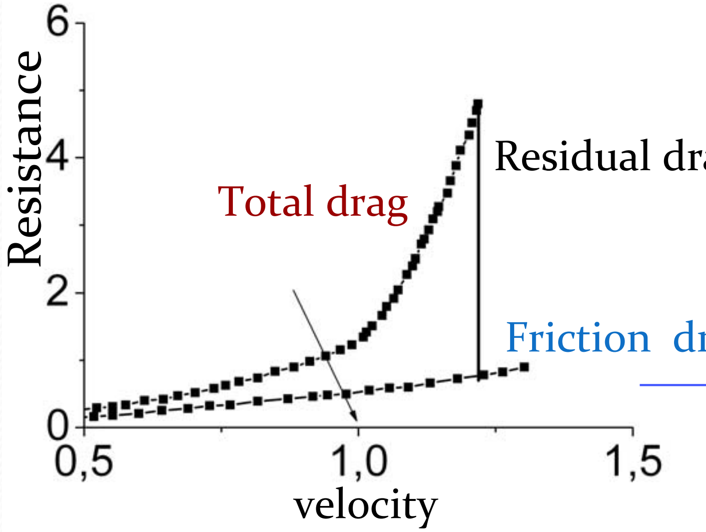
The water flow passes undisturbed and the origin of the resistance is the friction between the water molecules and the surface

During the motion , the sheet must open a road between the molecules of fluid; water molecules are gathering in front of the plate and thin out around the same time,





This produces a pressure difference corresponding to a force in the motion



physics

Total drag

- Friction
- Pressure or residual
  - Shape or wake
  - Wave drag
  - Vortex drag

C_R

Methods to obtain C_R

- Experimentals
  - In air: wind tunnel
  - In water: towing tank
- Numerical: CFD

Measurements on flat plate

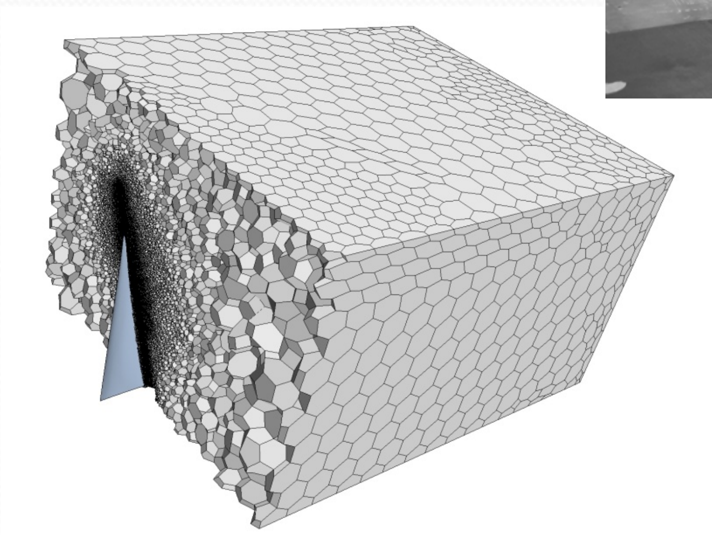
- Are relatively easy
- You can determine the ideal conditions in which the nature of the flow, laminar or turbulent stretches across the plate
- Can distinguish between friction drag and pressure drag

Measurements on the hull or sail

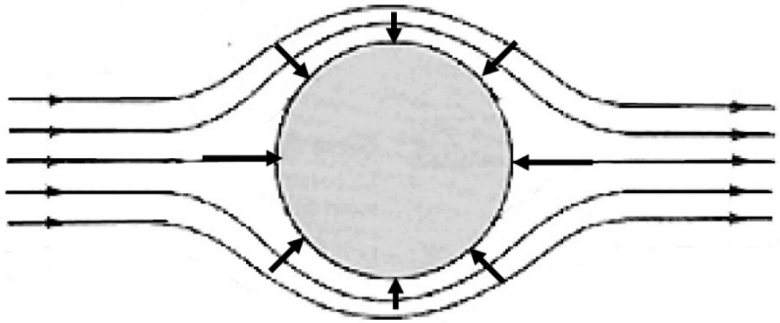
↓

One evaluates only the total resistance





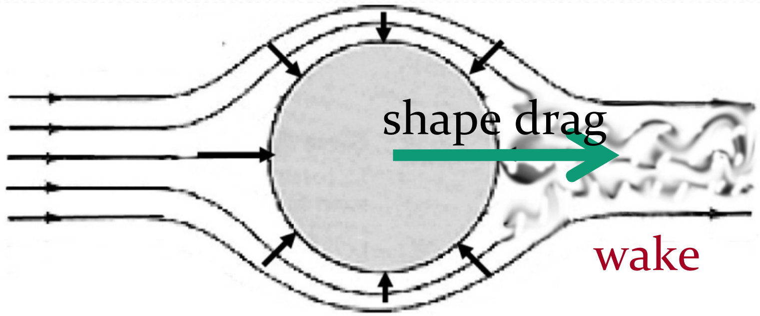

Shape or wake drag



Cylinder still in a real fluid

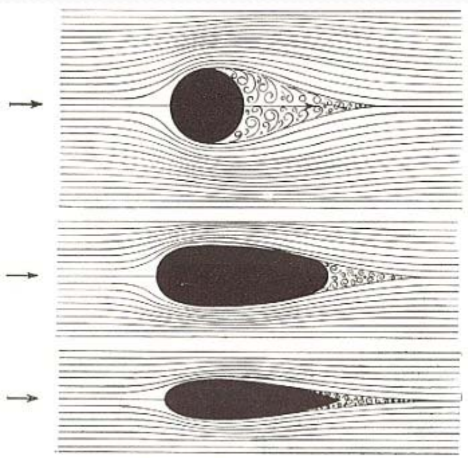
Ideal (not viscous) fluid moving around a cylinder: an ideal fluid does not undergo a loss of speed and it has enough energy to run parallel to the cylinder

the distribution of pressure is symmetric



Real (viscous) fluid moving around a cylinder: Because se of the viscosity, the fluid slows down, the boundary layer breaks down and separates

a wake is formed and the pressure in front and behind the cylinder are different



Larger wake

Higher drag

It depends on shape of the object

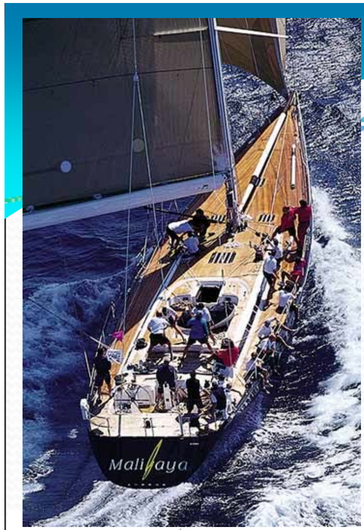
least resistance

Laminar or turbolent?

The laminar flow is slower than the turbolent , so the boundary layer separates in advance

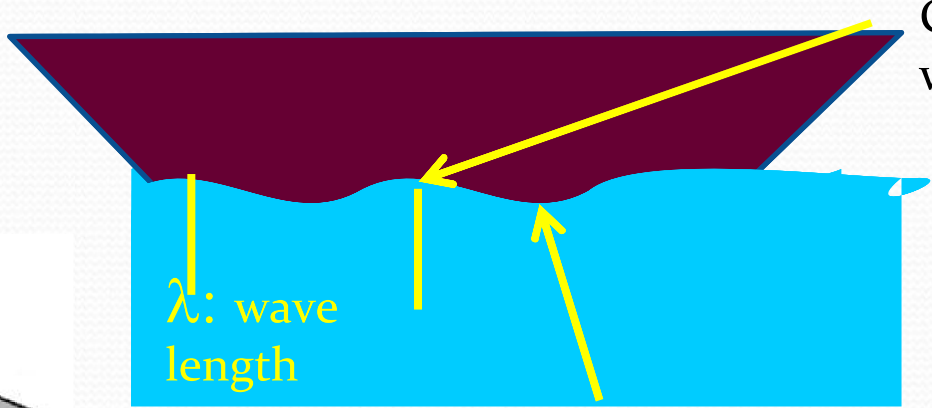
Artificial turbulence is created: holes in golf balls

Wave drag

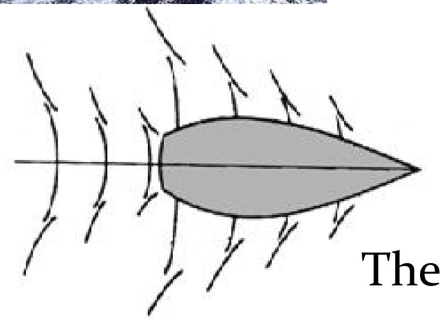


the hull while in motion moves water

Crest: water accumulates with an increase in sea level



Depression: water drops with a reduction in sea level

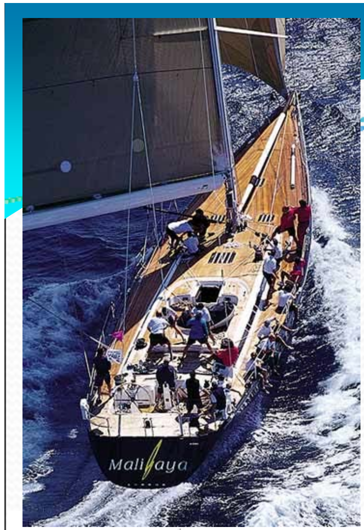


The waves carrie energy that is as large as the wave is high

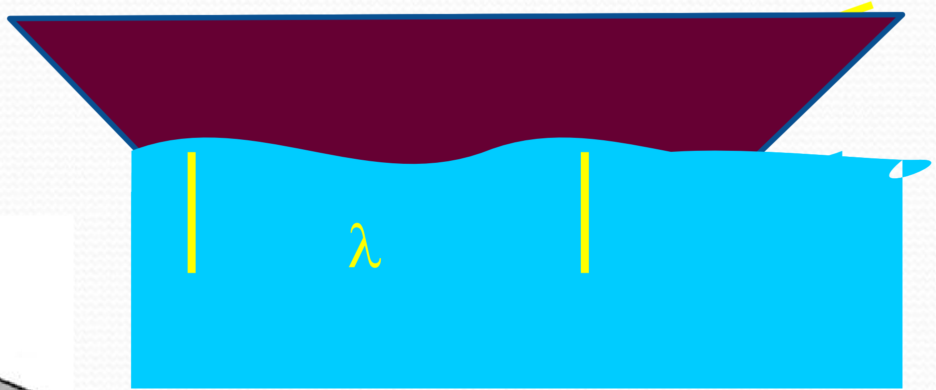
Where does it take this energy?

By the motion of the boat → Wave Drag

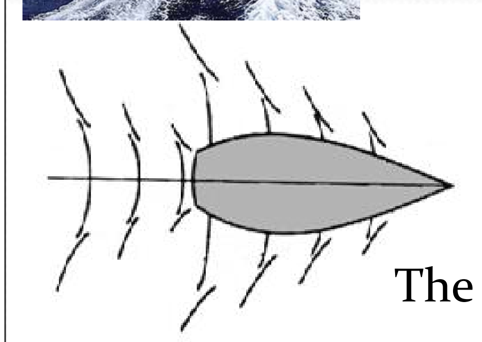
Wave drag



the hull while in motion moves water



$$\lambda = 2\pi \frac{\boldsymbol{V}^2}{\boldsymbol{g}}$$



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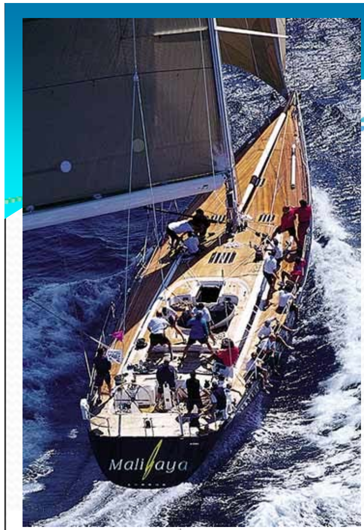
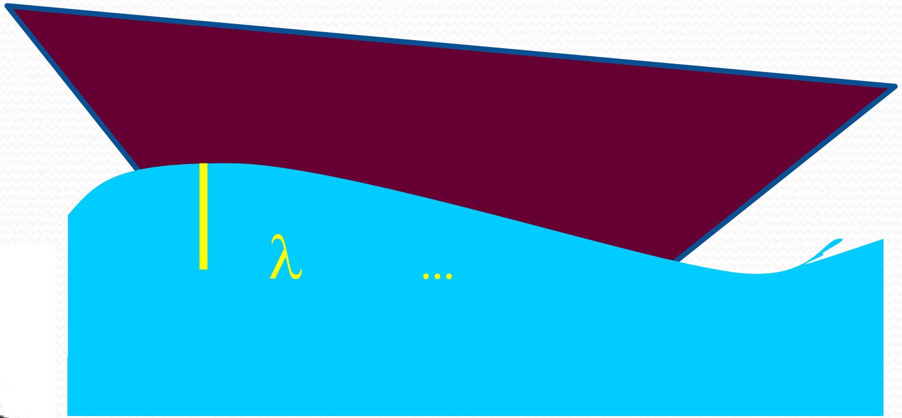
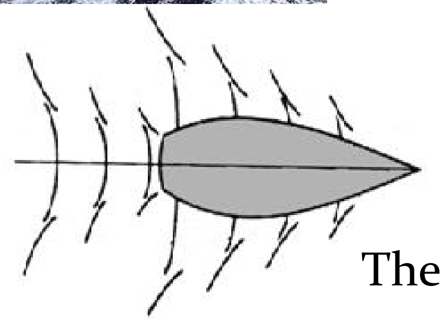
Wave drag



the hull while in motion moves water



$$\lambda = 2\pi \frac{\boldsymbol{V}^2}{\boldsymbol{g}}$$



The waves carrie energy that is as large as the wave is high

Where does it take this energy?

By the motion of the boat ➡ **Wave Drag**

If the wavelength exceeds that of the hull, the boat "falls" with the stern in the depression.
In these conditions, the resistance becomes impossible to overcome.
We then reach a critical speed

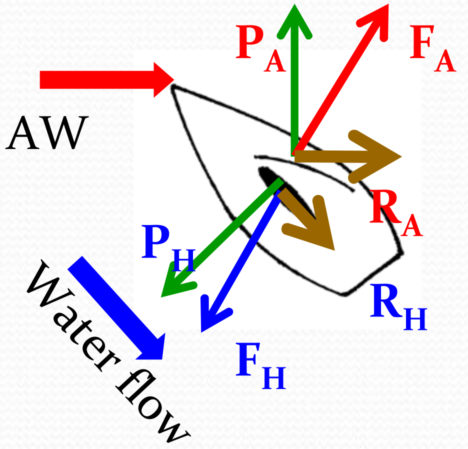
$$\boldsymbol{V}_c(\text{m/s}) = 1{,}25\sqrt{\boldsymbol{L}(\text{m})}$$

$$\boldsymbol{V}_c(\boldsymbol{knots}) = 2{,}4\sqrt{\boldsymbol{L}(\text{m})}$$

$$\boldsymbol{V}_c(\boldsymbol{Knots}) = 1{,}34\sqrt{\boldsymbol{L}(\text{f})}$$

Lift

The airplanes fly, or the shots on goal

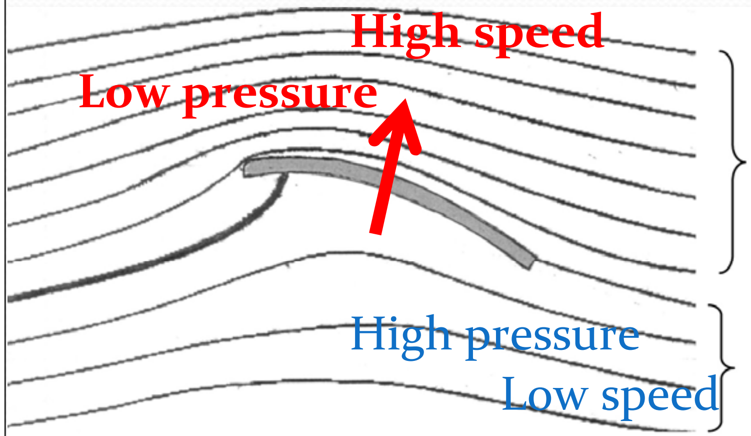


Component of the forces perpendicular to flow

P_H → Only if the boat making leeway

P_A → Lets go upwind

Flux lines around a sail without mast

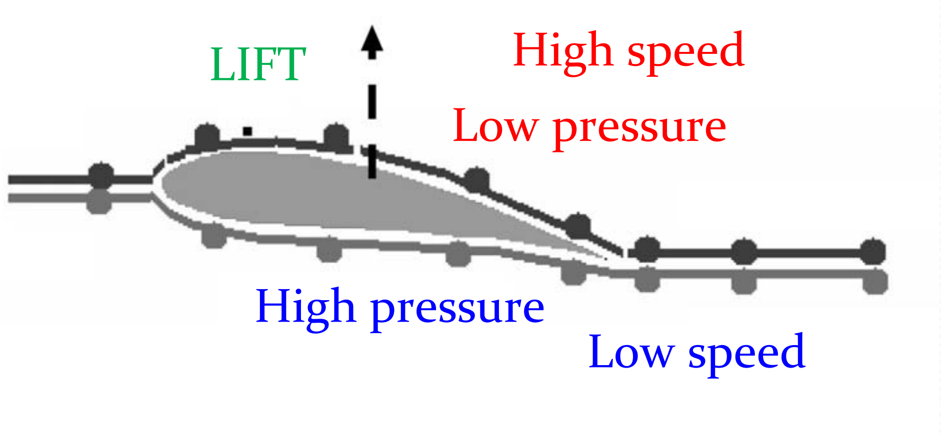


Low line density	Large line density
↓	↓
Low speed	High speed
↓	↓
High pressure	Low pressure

Bernoulli theorem $$p + \frac{1}{2}\rho V^2 = const$$

No corrected model

Theory of equal transit



Difference in pressure produces lift

Top of the airfoil is shaped to provide longer path than bottom.

Not always correct : the flat plate? And the card out of the window?

Air molecules must move faster over the top to meet molecules at the trailing edge that have gone underneath

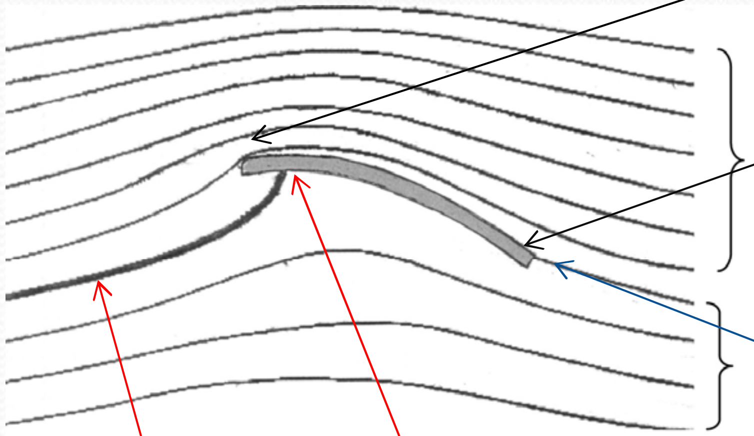
Non-physical assumption

... But why airplanes can fly upside down?

To understand how to generate lift

It must carefully analyze the flow lines around the sail

Many lines move downwind
At the luff the air has a deflection upwards



At the leech the air deflects downward

Downwind

windward

This stagnation line exits following
The sail curvature

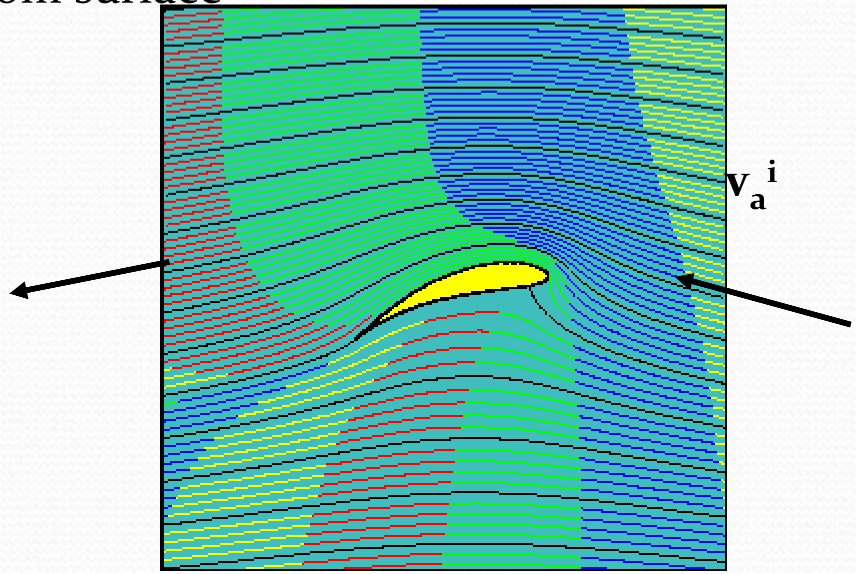
Stagnation line and point

The stagnation point at the entrance is in the windward zone: part of air that should go windward, is thrown downwind and follows the curvature of the sail

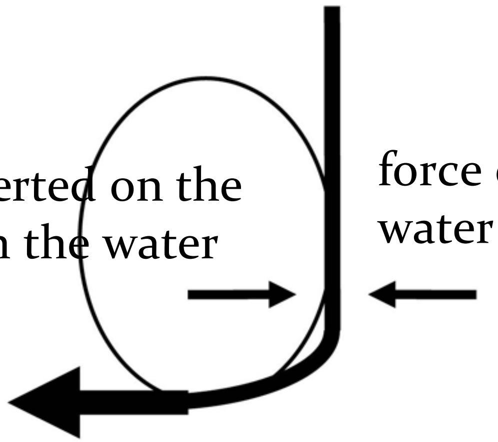
Why?
Because of the viscosity

Coanda effect

The viscosity of the fluid blocks the first layer of water molecules in contact with the egg. Molecules of the second layer, attracted by the first, rotate . Successive layers rotate less and less as one moves away from surface

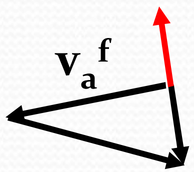


The water follows the curve surface:



$\Delta v_a = v_a^f - v_a^i$

$\Delta v_a / \Delta t = a_a$

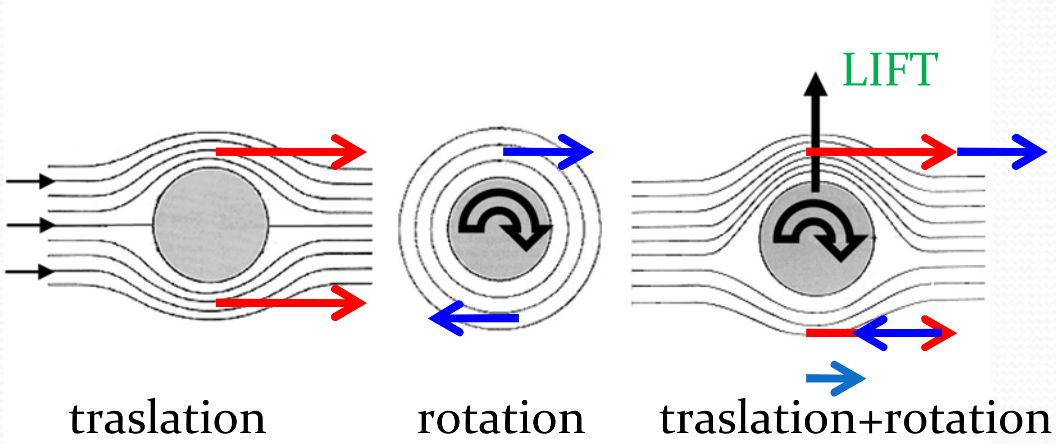


$F_p = -F_a$

$F_a = m a_a$

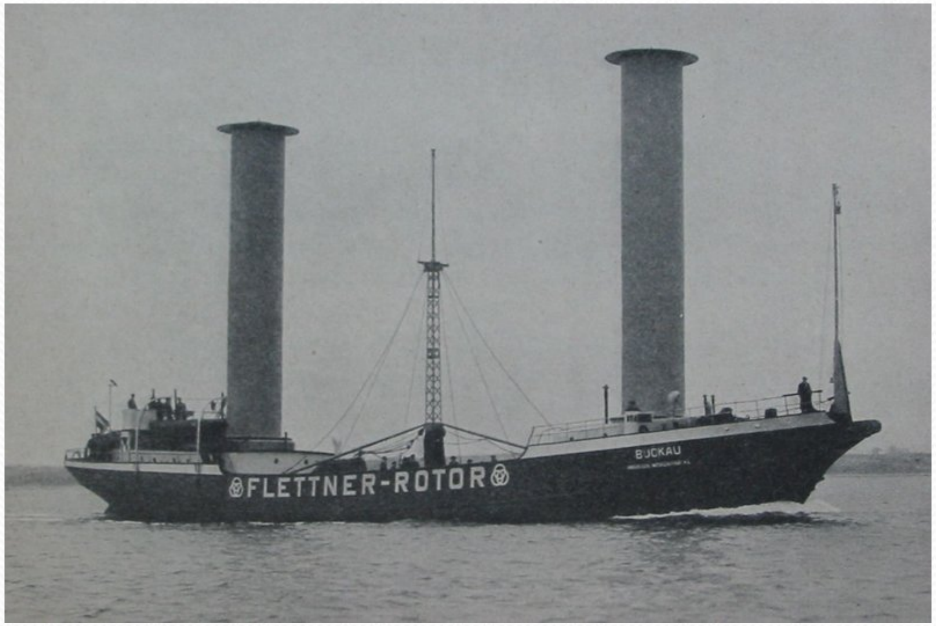
Magnus effect

Or the goal with shot effect

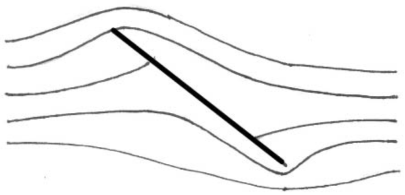


if you throw a ball giving it a certain rotation it deflects

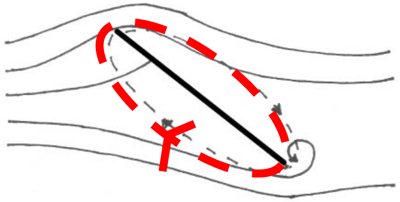
1922 – BUCKAU



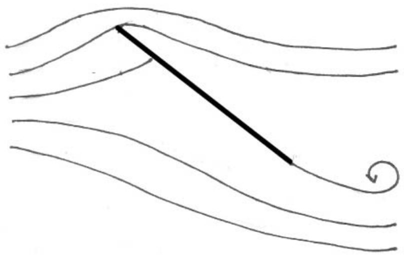
...on a flat plate



Traslation: air passing over is the same as under.



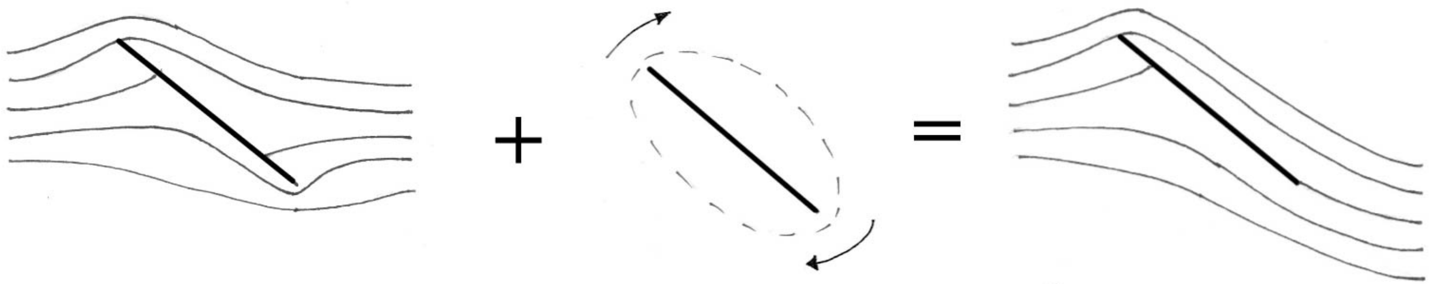
At the trailing edge the fluid separates forming a wake and creating an anticlockwise vortex



The stagnation point in the upper surface will displace up to coincide to the trailing edge

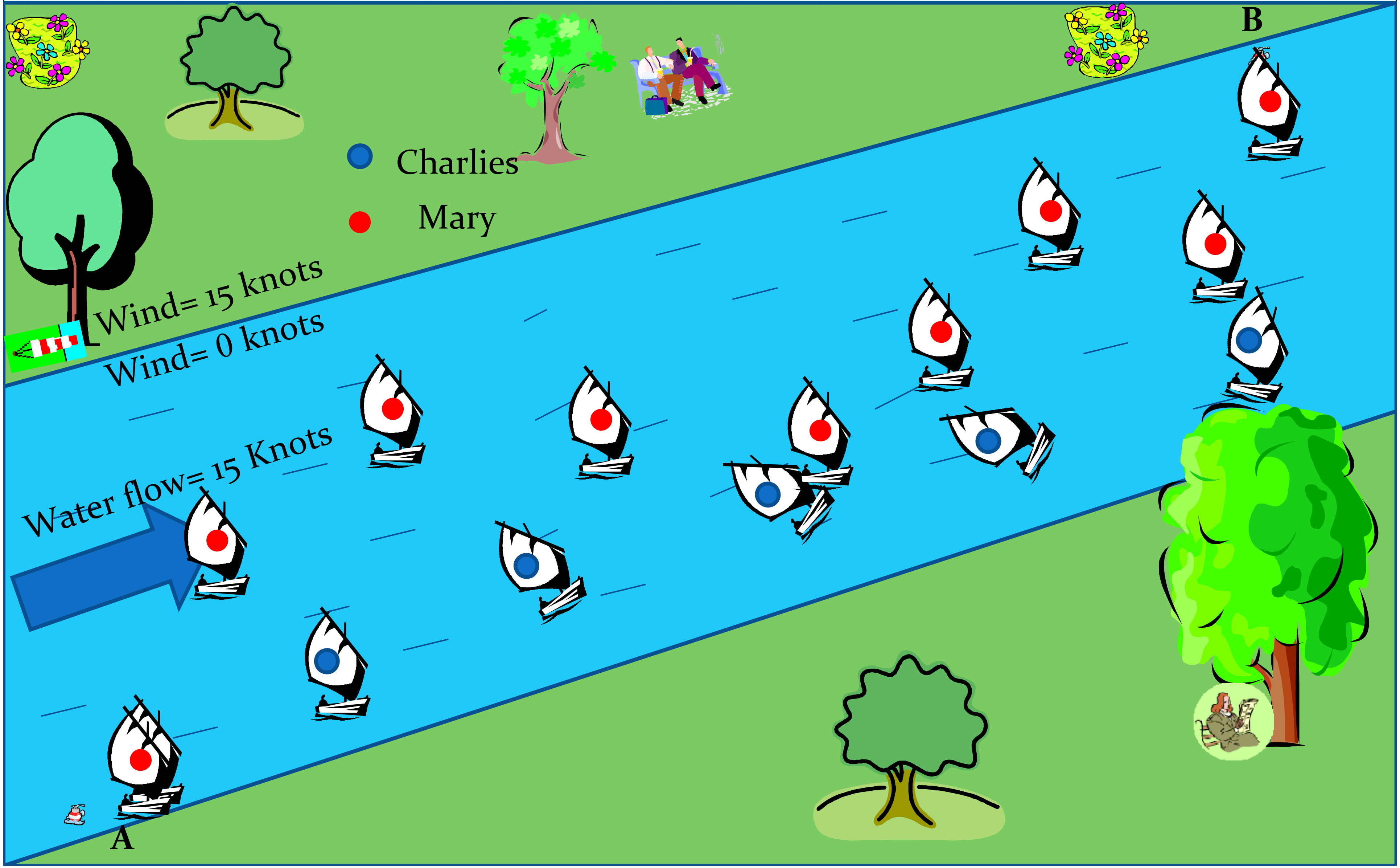
To the anticlockwise vortex corrisponds a clockwise one (Helmoltz theorem)

Analogy with the rotating cilinder



Also if the plate and the wing do not rotate, due to the viscosity, the air has a circular motion

Conclusions



"There is nothing that gives even half the pleasure that you try to go for a walk on board a boat."
(The Wind in the Willows, Kenneth Grahame)

GOOD WIND TO EVERYBODY!