DESIGN TO WIN

ARIANNA BIONDA - POLITECNICO DI MILANO - YACHT DESIGN AND MARITIME TECH

WHAT DO THEY HAVE IN COMMON?

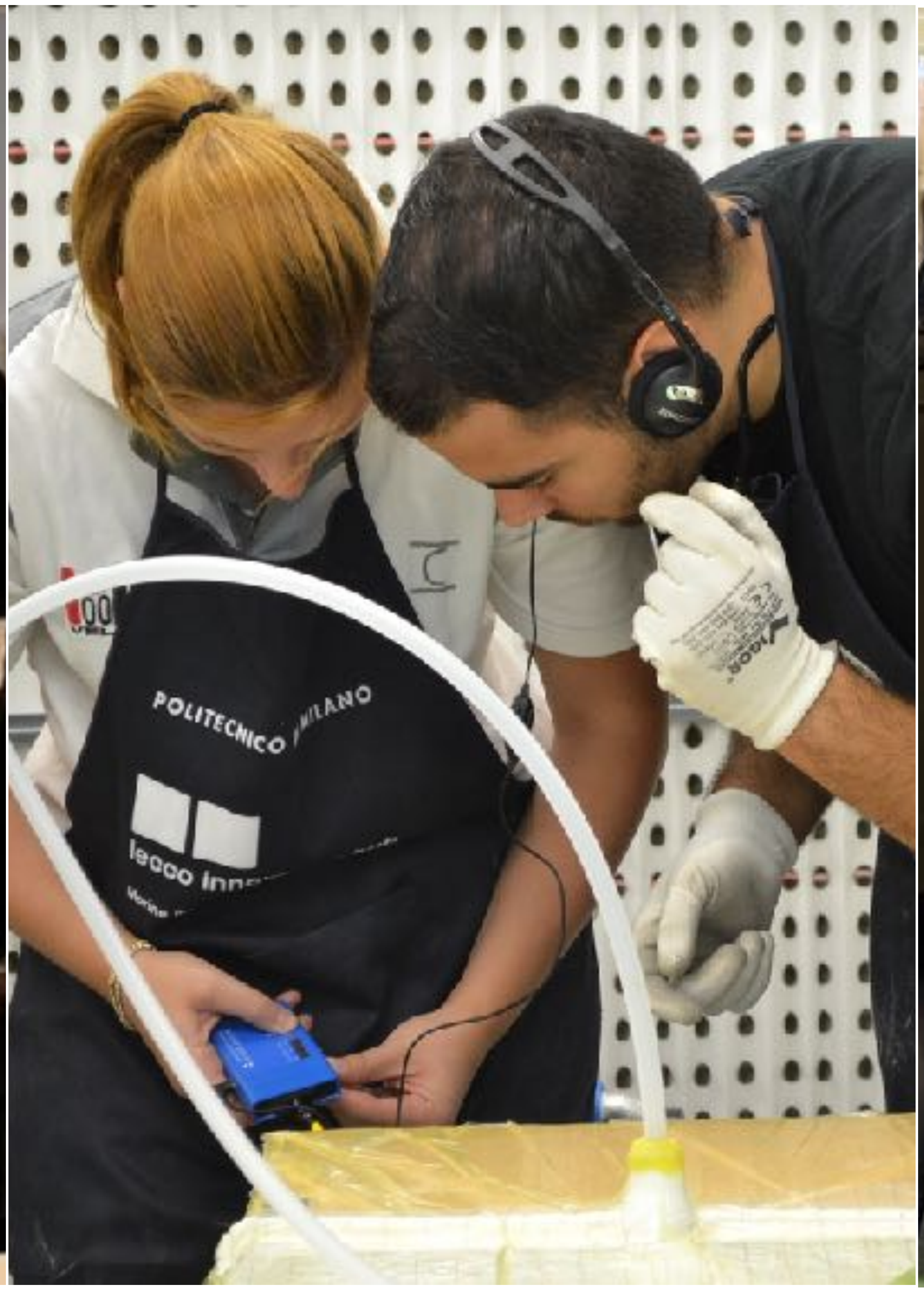

WHAT DO THEY HAVE IN COMMON?
SMART TRADE-OFFS
RULE EXPLOITATION
TECH
SIMULATIONS
INNOVATION
PERFORMANCE

PERFORMANCE IN A RACE DEPENDS ON THE TEAM'S ABILITY TO UNDERSTAND THE PHYSICS THAT GOVERN THE BEHAVIOUR OF THE BOAT IN THE WATER

James Allison

INEOS Britannia AC, Design Leader

Mercedes F1 Team ,Technical Director



ARCHITECT AND SAILOR
PHD IN DESIGN
RESEARCHER AT POLITECNICO DI MILANO

Yacht Design and Maritime tech group Leader
Project Manager Polimi Sailing Team
Vice Director of MYD – Master in Yacht Design


AITITIA
NEO 350
ORC


TECHNE
TRE1/2
BAUSCIA
FA BALA L'OCC
SCARLIGA
32
1001VELA CUP


THETIS
PEBE
SUMOTH

PLAY WITH THE RULES

DEEPLY UNDERSTANDING THE REGULATIONS AND THE BEHAVIOUR OF OBJECTS WITHIN A SYSTEM, THEN CREATIVELY PUSHING THE BOUNDARIES

(STAYING WITHIN THE RULES BUT EXPLOITING EVERY POSSIBLE ADVANTAGE TO MAXIMISE PERFORMANCE AND INNOVATION)

The America's Cup is a sailing competition and the oldest international competition still operating in any sport (since 1851).

For over a century, the NYYC successfully defended the Cup until Australia II broke the streak in 1983. Since then, teams from United States, United Kingdom, Australia, New Zealand, Switzerland, Italy, Sweden, France, Spain, South Africa, and Canada. have battled for supremacy in this prestigious event.



AMERICA'S CUP
BARCELONA
FLY BETTER
Emirates
OMEGA
TOYOTA
Emirates
FLY BETTER
OMEGA
ESTRELLA
Emirates
TOYOTA
OMEGA

THE RULES

DEFENDER VS. CHALLENGER FORMAT – "THERE IS NO SECOND, YOUR MAJESTY"!

- One-on-one races between two boats
- The defender (the team that won the last Cup) automatically qualifies for the final race.
- The challengers must compete in the Challenger Selection Series (e.g., the Louis Vuitton Cup) to determine who faces the defender.

WHO WIN DECIDE

- The defender decides the rules (type of boats)
- The challenger of records (first arrive) decide where and when

NATIONALITY

- The majority of the crew must be citizens (min. 3 yrs) or residents of the country they represent
- Boats must be built within the country they represent (ensuring national involvement)


PRADA

Moth Class is one of the oldest development classes in sailing (sailors and designers can experiment with different designs as long as they meet basic class rules).

The International Moth Class began in the 1920s in Australia as a low-cost, home-built sailing dinghy.

Over time, the class evolved into one of the most technologically advanced foiling sailboats in the world.
In the 2000s, hydrofoils were introduced, revolutionizing the class by allowing boats to "fly" above the water, reducing drag and increasing speed.


3


KA
9013


NZL
4740
PELLE
GARMIN

THE RULES

SINGLE HANDED

-just one sailor onboard

BOX RULES (SIZE LIMITS)

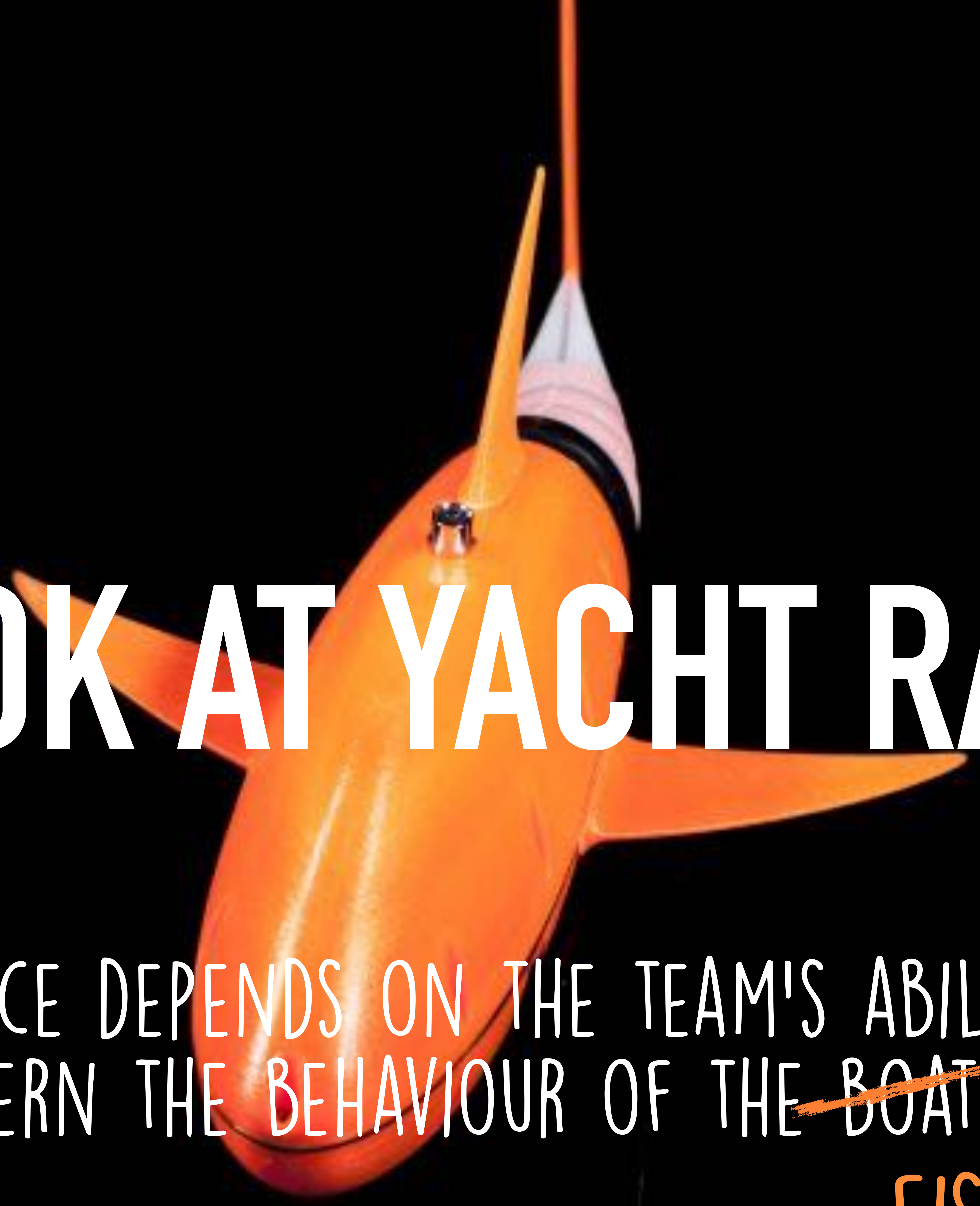
- Length: max 3.355 meters (11 feet)
- Beam: max 2.43 meters (8 feet)
- Sail Area: max8.25 square meters


"RATING SYSTEM HAVE MUCH MORE INFLUENCE UPON THE SHAPE OF YACHTS THEN THE SEA WITH ALL HER FICKLENESS. RATHER THE HISTORY OF THE RACING YACHT IS RACE AGAINST THE RULES THAN AGAINST THE SEA"
Phillips-Birt
Sailing Yacht Design, 1951
SUI 4896
AUS 4988
AUS 4247

WHO WIN?

- The one who gets foiling first (gets first in the asset)
- The one who is faster at changing direction and regaining the asset
- The one who doesn't break (reliable boat/systems/components)

WHY LOOK AT YACHT RACING?



WHY LOOK AT YACHT RACING?

PERFORMANCE IN A RACE DEPENDS ON THE TEAM'S ABILITY TO UNDERSTAND THE PHYSICS THAT GOVERN THE BEHAVIOUR OF THE ~~BOAT~~ FISH IN THE WATER

UNDERSTANDING

domains	yacht	fish
HYDRODYNAMICS	HULL SHAPE / FOILS	FISH BODY, FIN GEOMETRY
PROPULSION	SAIL, APPARENT WIND USE	TAIL PROPULSION / FIN MOVEMENT
NAVAL ARCHITECTURE	WEIGHT DISTRIBUTION	BUOYANCY CONTROL, MASS DISTRIBUTION
SYSTEMS	STABILITY, CONTROL SYSTEMS	SENSORS, ACTUATORS
MANOUVERING	FOIL ANGLE ADJUSTMENTS	FIN/TAIL ANGLE CONTROL
MATERIALS AND CONSTRUCTION	LIGHTWEIGHT COMPOSITES	WATERPROOF, LIGHT CONSTRUCTION

PRINCIPLES FOR SAILING BOAT RACING DESIGN

The design of Sailing yachts - YD spiral
Basic of Hydrostatics
Center of buoyancy and gravity
Speed vs hull form
How to scale

NAVAL ARCHITECTURE

HYDROSTATICS

-

APPENDAGES DESIGN

Keel and rudder vs fin vs foils
NACA profiles
Aspect ratio and how to chose
Tip types and why

HYDRODINAMICS

-

PRINCIPLES FOR SAILING BOAT RACING DESIGN

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APPENDAGES DESIGN

Keel and rudder vs fin vs foils
NACA profiles
Aspect ratio and how to chose
Tip types and why

PRIORITISE YOUR WINNING STRATEGY

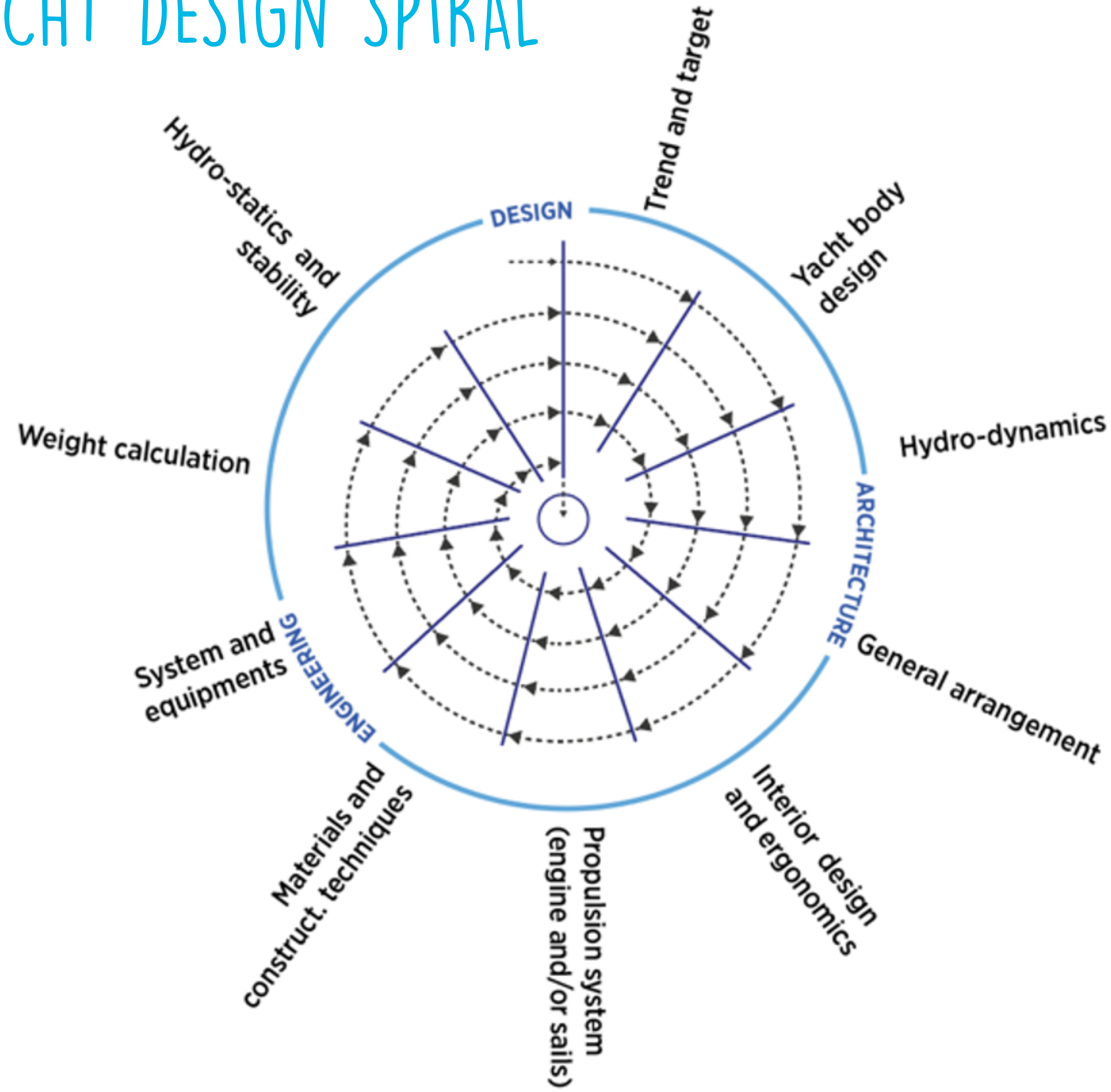
CONTROL THE ASSET

CORRECT PROTOTYPING ISSUES

SCALE YOUR DESIGN

CHOSE FIN DESIGN

YACHT DESIGN SPIRAL



Yacht Design is the art and science of designing yacht and ships to perform the missions and to meet the requirements laid down by the prospective owners and operators (or race rules).

It is an iterative process where the final results has to deal with a compromise between a lot of factors, with no explicit values. It is an intuitive trial-and-error process in which physics of sails, naval architecture, ergonomics, mechanical engineering and production methods, and aesthetics plays a role.


"A VESSEL MUST BE LIGHT ENOUGH TO BE DRIVEN EASILY BY A MODERATE BREEZE, STIFF ENOUGH TO STAND UP TO HER CANVAS IN HARD WIND, SHALLOW ENOUGH TO BE AND TO RUN WITH SPEED. SHE MUST HAVE DEPTH ENOUGH TO HOLD HER UP TO WINDWARD, BREADTH ENOUGH TO GIVE HER STABILITY; SHE SHOULD BE LONG ENOUGH TO REACH WELL, AND SHORT ENOUGH TO TURN WELL, WITH PLENTY OF FREEBOARD TO KEEP THE SEA OFF HER DECKS. SHE MUST BE BROAD, NARROW, LONG, SHORT, DEEP, SHALLOW, TENDER, STIFF. IT IS NOT STRANGE THAT DESIGNERS PASS SLEEPLESS NIGHTS, AND THAT ANYTHING LIKE FINALLY AND PERFECTION OF TYPE IS IMPOSSIBLE TO CONCEIVE."
Lord Dunraven
Challenger AC 1893-1895

NAVAL ARCHITECTURE – BASICS OF HYDROSTATICS

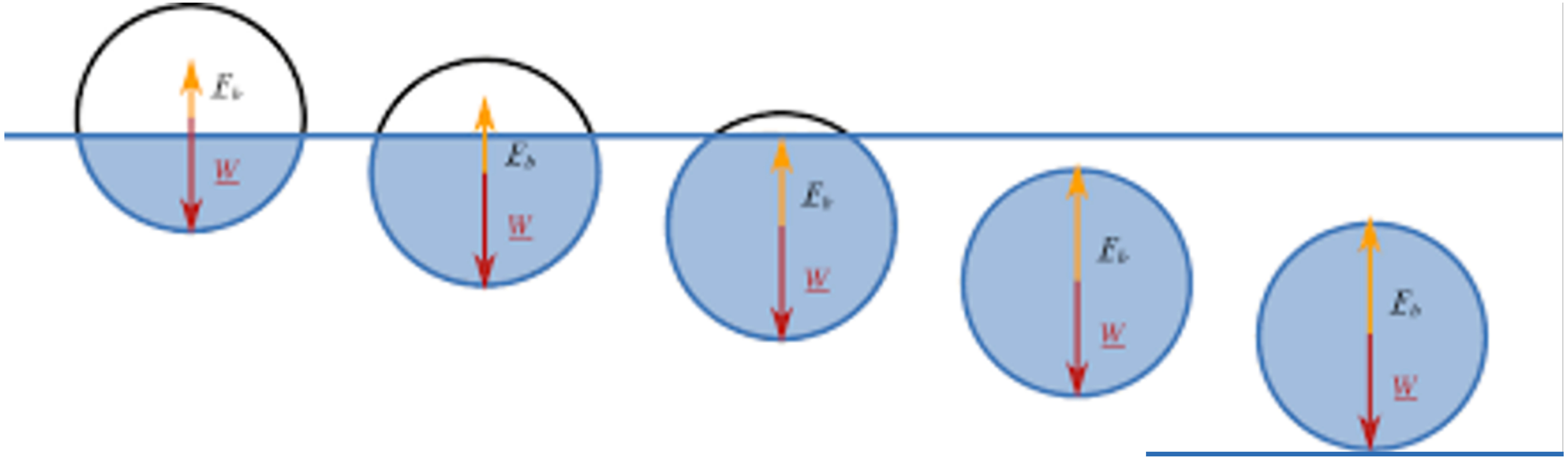
ARCHIMEDE'S PRINCIPLE:
An object can float when the mass of water that it displaces (pushes out of the way) is equal to the mass of the object. This displaced water causes an upward force called buoyancy.

If the buoyant force is greater than the object's weight, the object will rise to the surface and float. If the buoyant force is less than the object's weight, the object will sink. If the buoyant force equals the object's weight, the object can remain suspended at its present depth (like submarines).

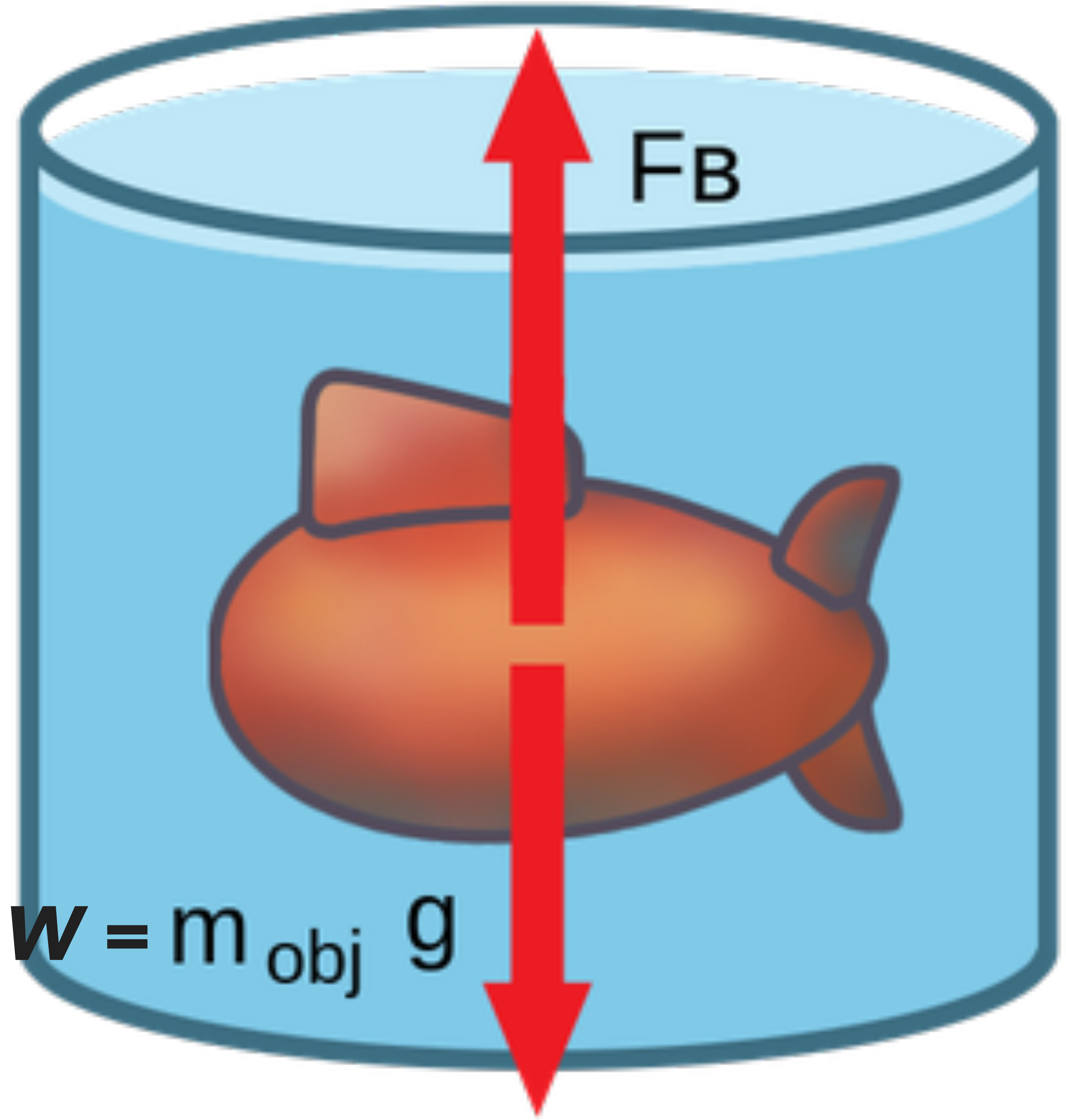
$$\Delta = V \times \gamma$$

Vessel displacement = vessel volume times water specific gravity *

γ Fresh water: 1000 kg/m³
Seawater: 1025 kg/m³



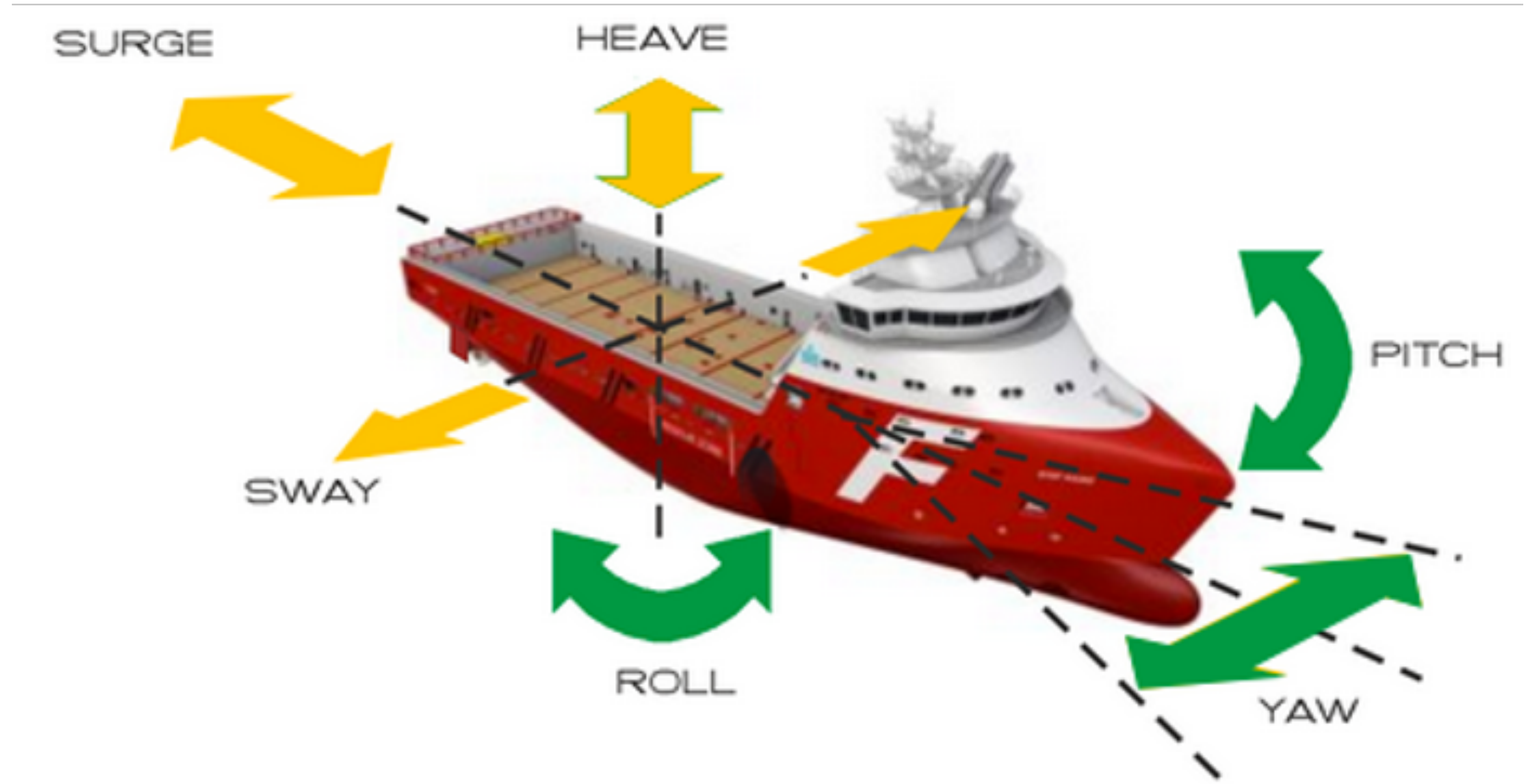
AN OBJECT FLOATING AT REST IN CALM WATER IS ACTED UPON BY TWO FORCES: WEIGHT AND BUOYANCY.

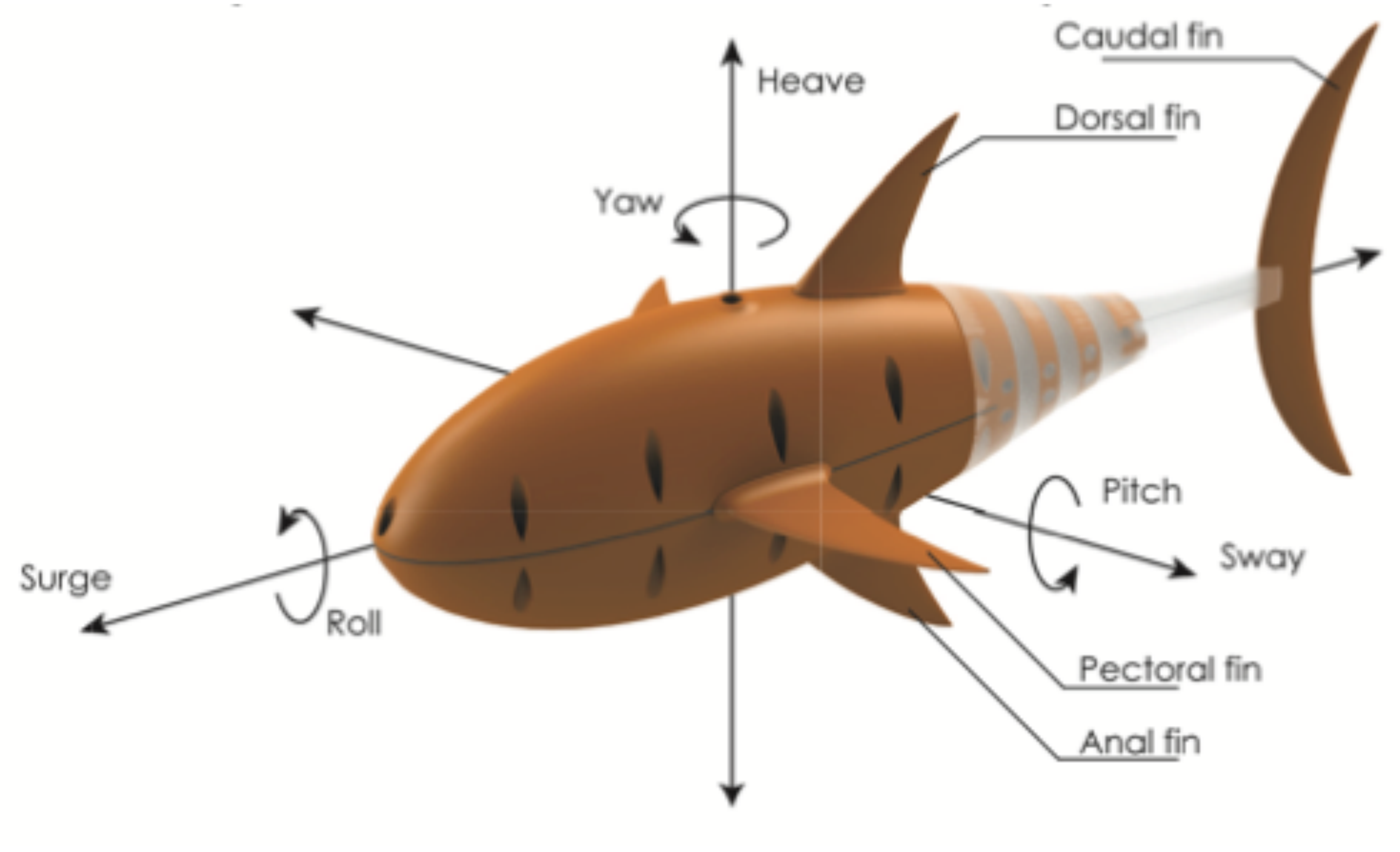


Weight is the downward force on the ship. The total weight force (W) acts on the ship as if it were concentrated at the balancing point or the centre of gravity (G).

Buoyancy is the upward force of all the hydrostatic pressures on the hull. The vertical components of the water pressures on unit areas combine to form an upward force (Fb) equal to the weight of the water displaced by the underwater hull volume. The centre of buoyancy (B) lies at the geometric centre of the immersed volume.

The ship sinks in the water until the force B exactly equals the force W, in accordance with Archimedes' principle.





A RIGID BODY IN WATER HAS 6 DEGREES OF FREEDOM:

TRANSLATION

- Heave (vertical)
- Surge (horizontal)
- Sway (transversal)

ROTATION

- Roll (around x, left-right tilting)
- Pitch (around y, bow-stern tilting)
- Yaw (around z, left-right rotation on the water plane)

WHY DOES SHE FLOAT?
HOW DOES SHE FLOAT?

CONTROL THE FISH ASSET

Life depends a lot on which monsters you take in your boat

THE BOAT THE FISH

Geometric hull definition

Principal Dimensions

Physical principles

Centre of buoyancy

THE MONSTERS

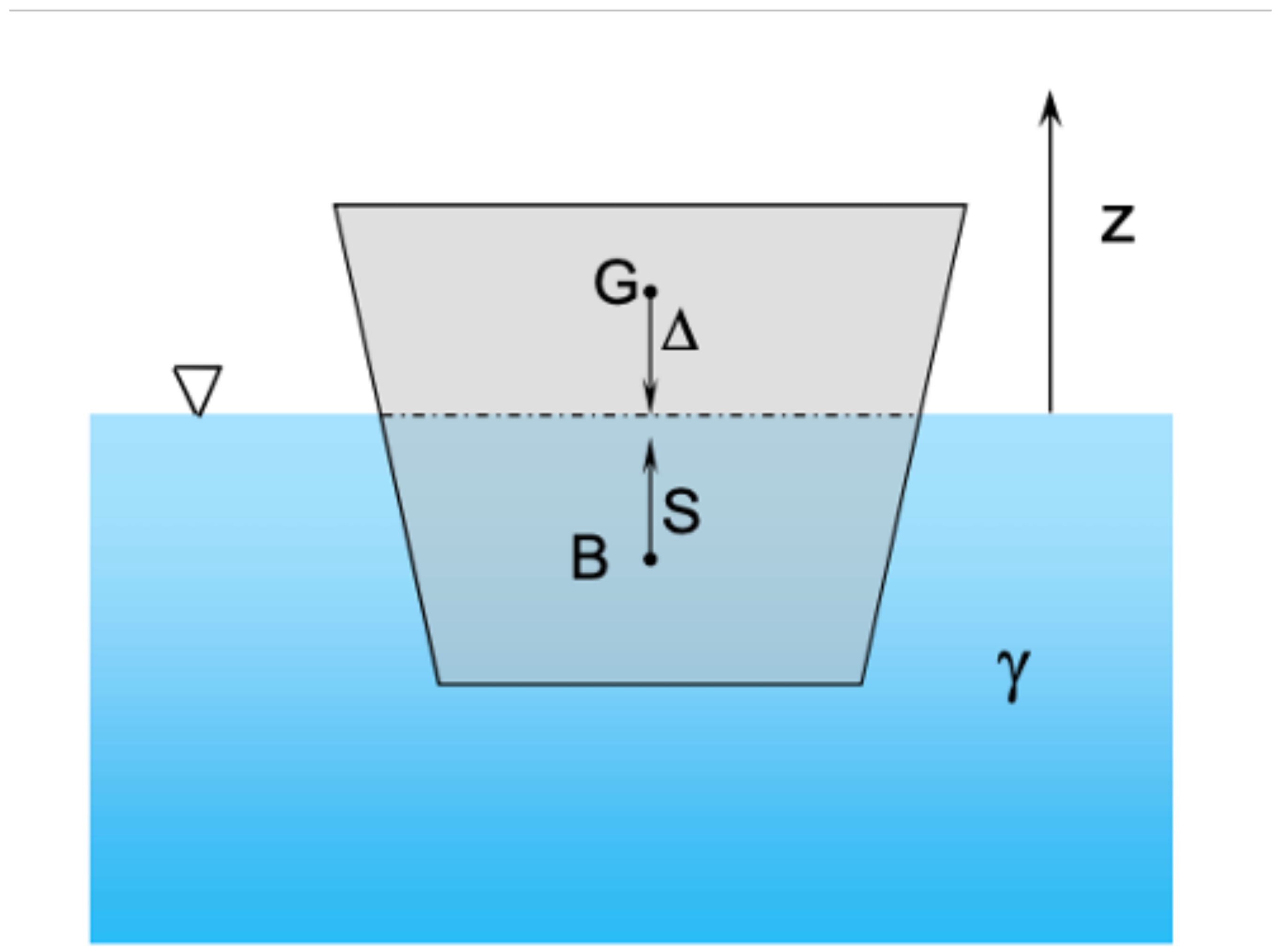
Weights from components

Centre of Mass position (Centre of Gravity calculation)

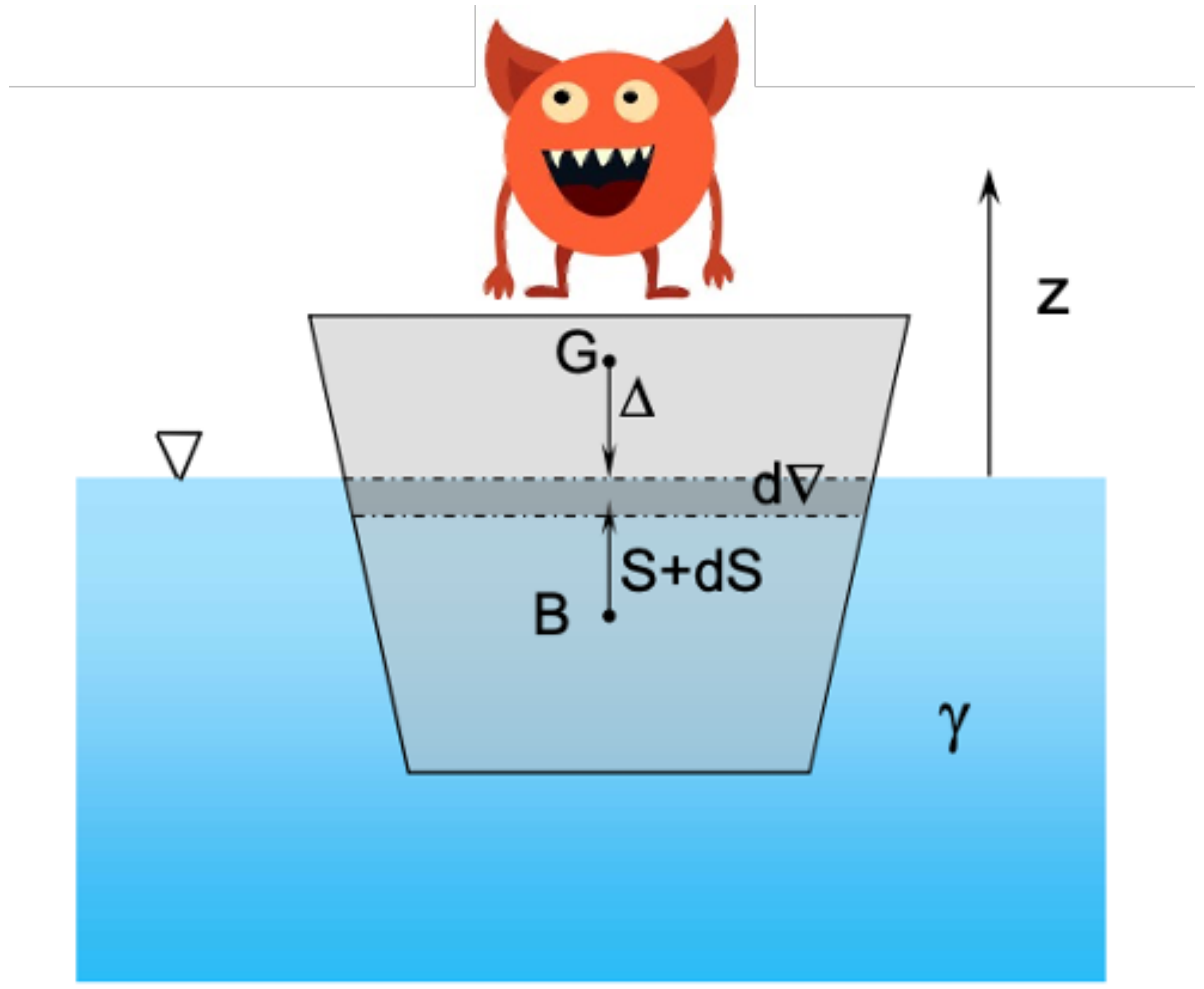
Dynamic weights (cargo and crew)

EQUILIBRIUM OF A FREE FLOATING OBJECT

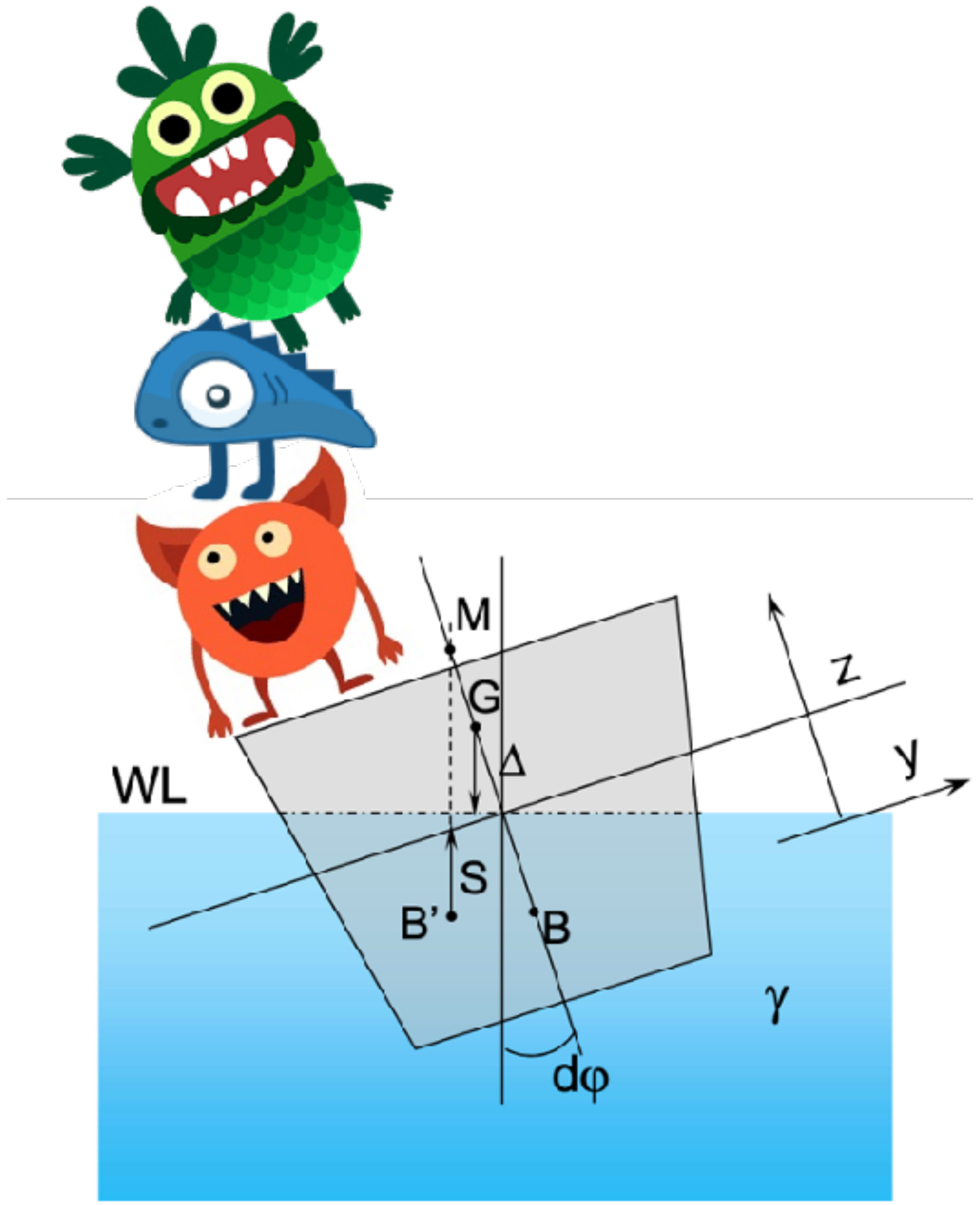
The asset (position of equilibrium of the body) is determined by the relative positions of G (center of gravity) and B (center of buoyancy). When weights (such as components, cargo, or crew) are moved onboard, the center of gravity shifts accordingly. As the vessel heels or trims in response, the center of buoyancy also moves laterally or vertically to reflect the new underwater volume shape. The center of buoyancy will adjust in accordance with the vessel's new orientation.



A floating body is in stable equilibrium in respect to the moving along axis z



If the boat weight increase
△ becames △ +d △
The immersed volume will produce the hydrostatic thrust S + dS
The system is in equilibrium again



If the boat weights change in position, G and B will change accordingly.

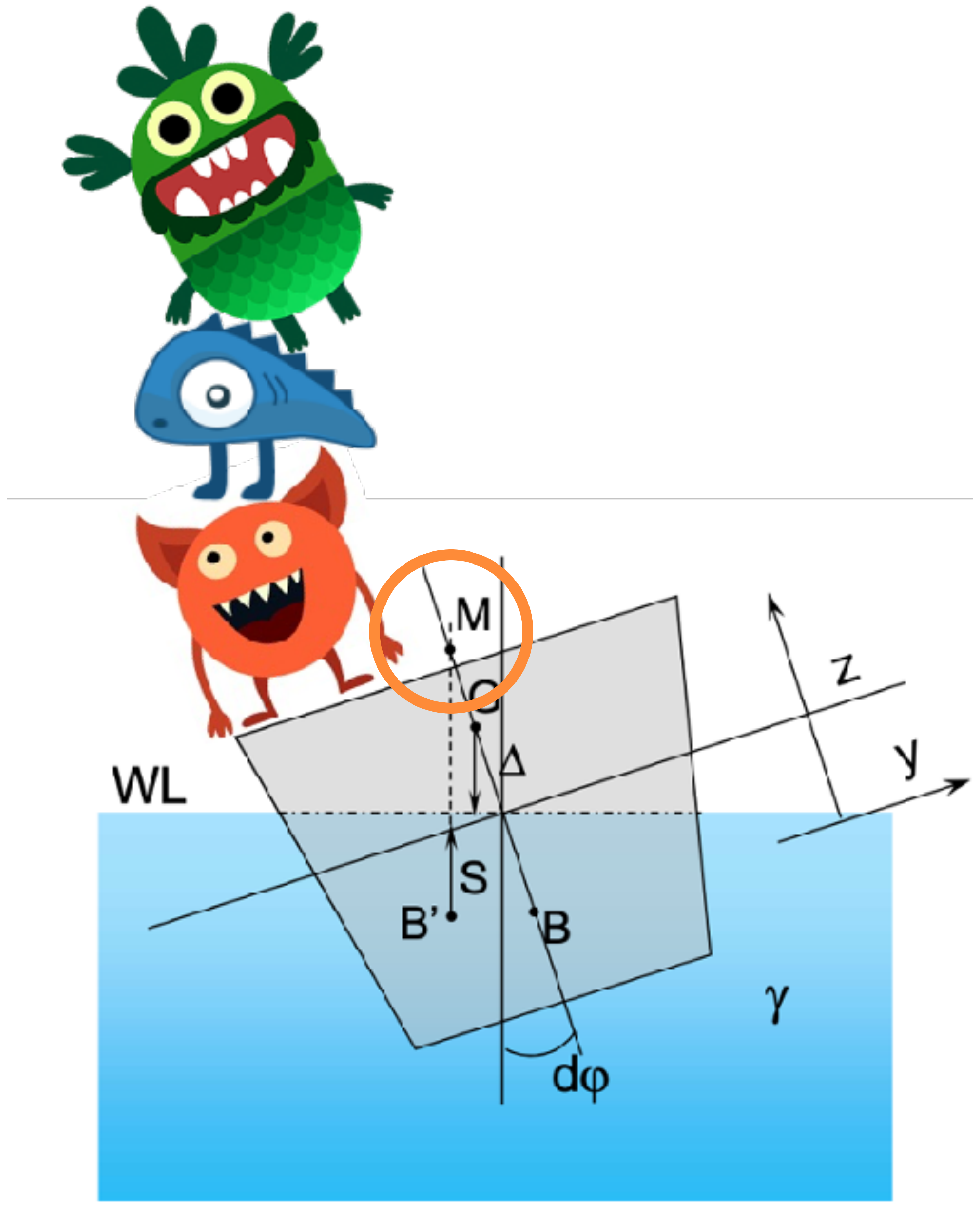
The center of rotation of the vessel body is called Metacentric. It is the point at which a vertical line through the heeled centre of buoyancy crosses the line through the original.

The distance between G and M is called the metacentric height (GM).

- Large GM
  Boat is more stable (but can make the ship roll quickly and uncomfortably) – Fish quickly returns upright when tilted. Good stability, but it might wobble or rock too fast.
- Small GM
  Boat is less stable (can be more comfortable, but might capsize easily) – The fish wobbles slowly and smoothly, but might not recover well from a tilt.
- Negative GM
  very dangerous (bad design): the ship/fish won't come back upright on its own – might need to restart or rescue it.

https://www.youtube.com/watch?v=QUgXf2Rj2YQ

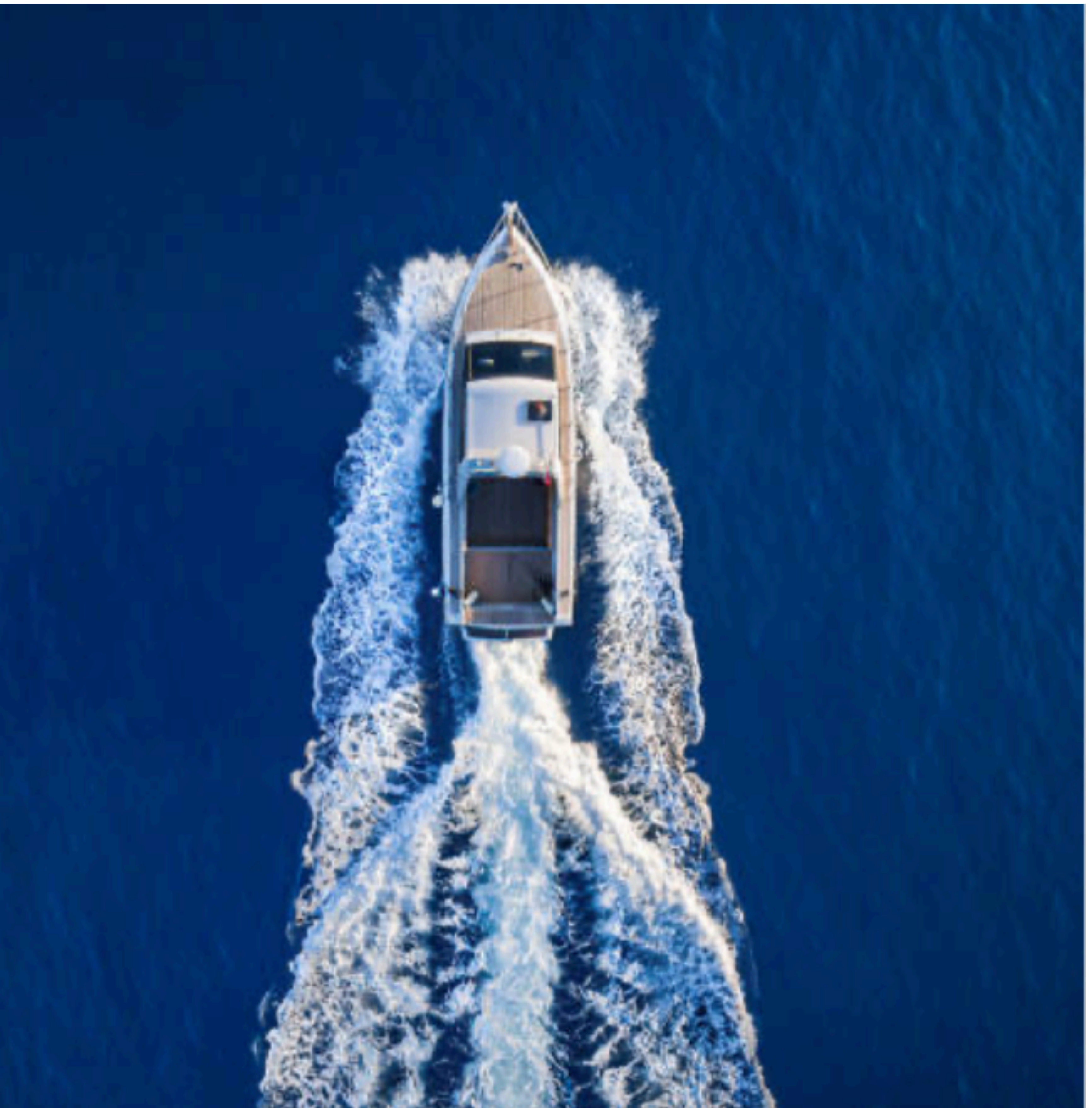
https://www.youtube.com/watch?v=Ypc4bapoGM8

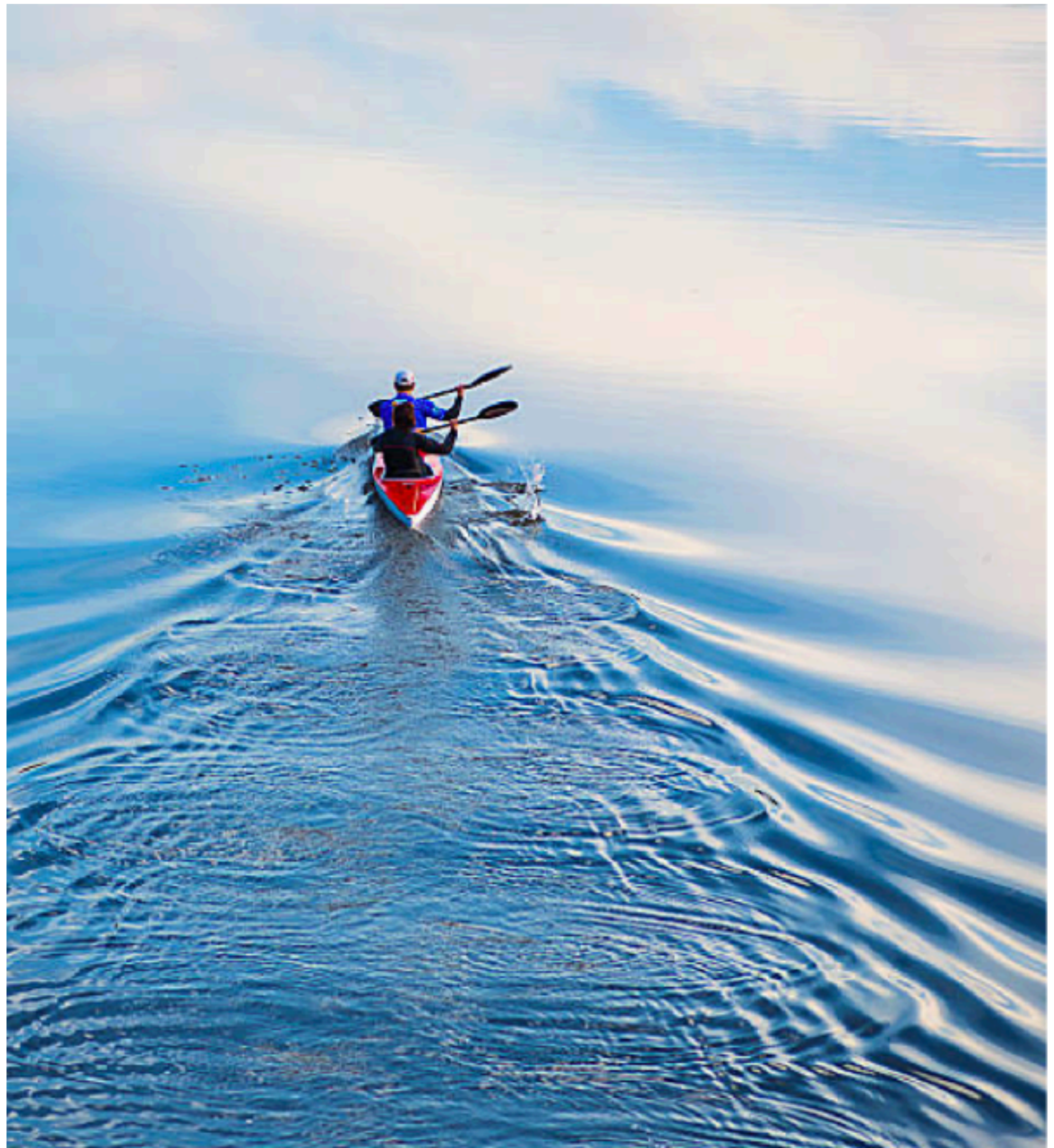


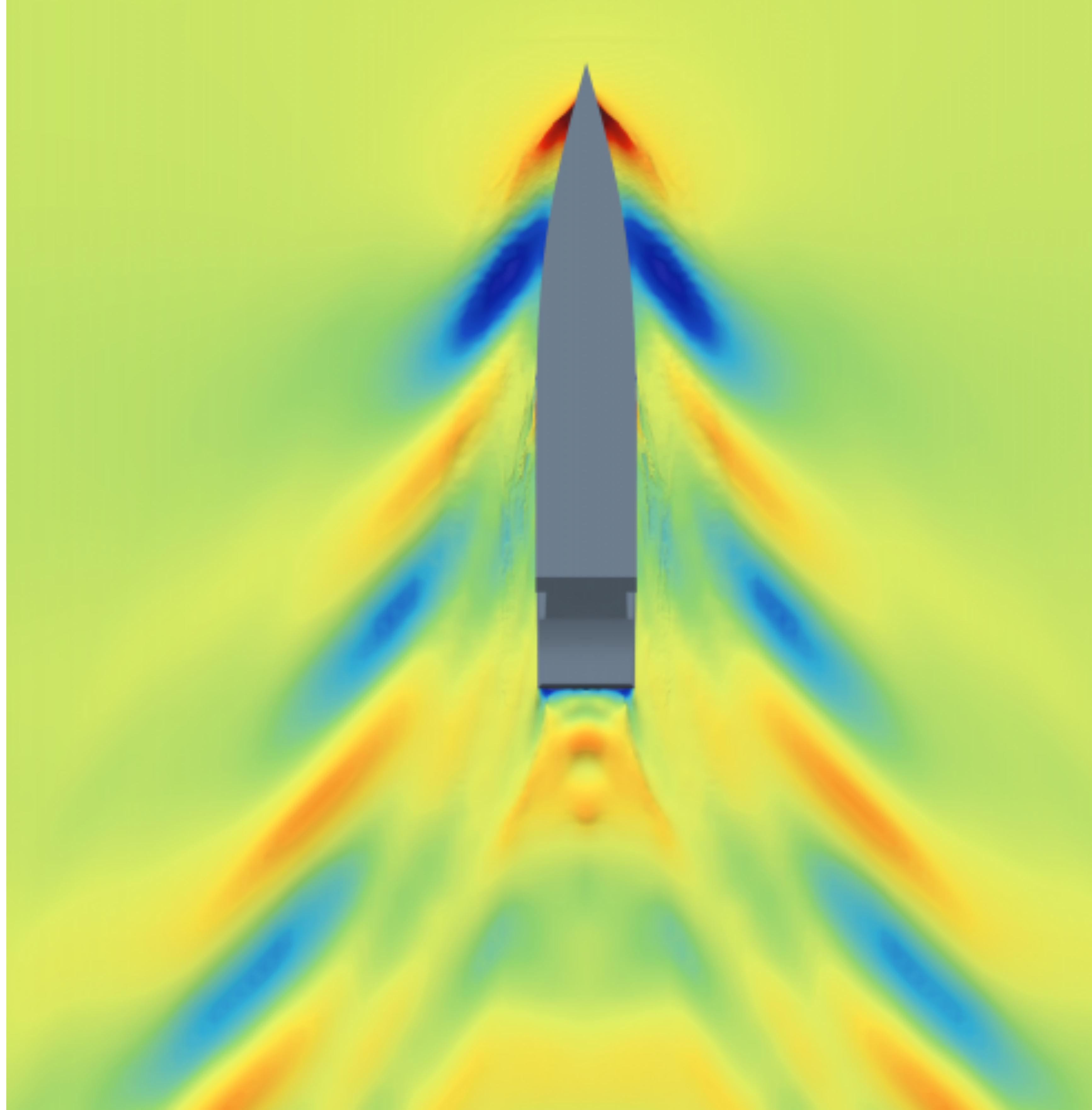
If the boat weights change in position, G and B will change accordingly.

NAVAL ARCHITECTURE – BASICS OF HYDRODYNAMICS

Boats can move into the water only if a force is applied to them (from sail, engine, humans). As an object moves through the water, the friction of the water acting over the entire wetted surface of the object causes a net force opposing its motion. This frictional resistance is influenced by the object wetted surface area, surface roughness, and water viscosity.



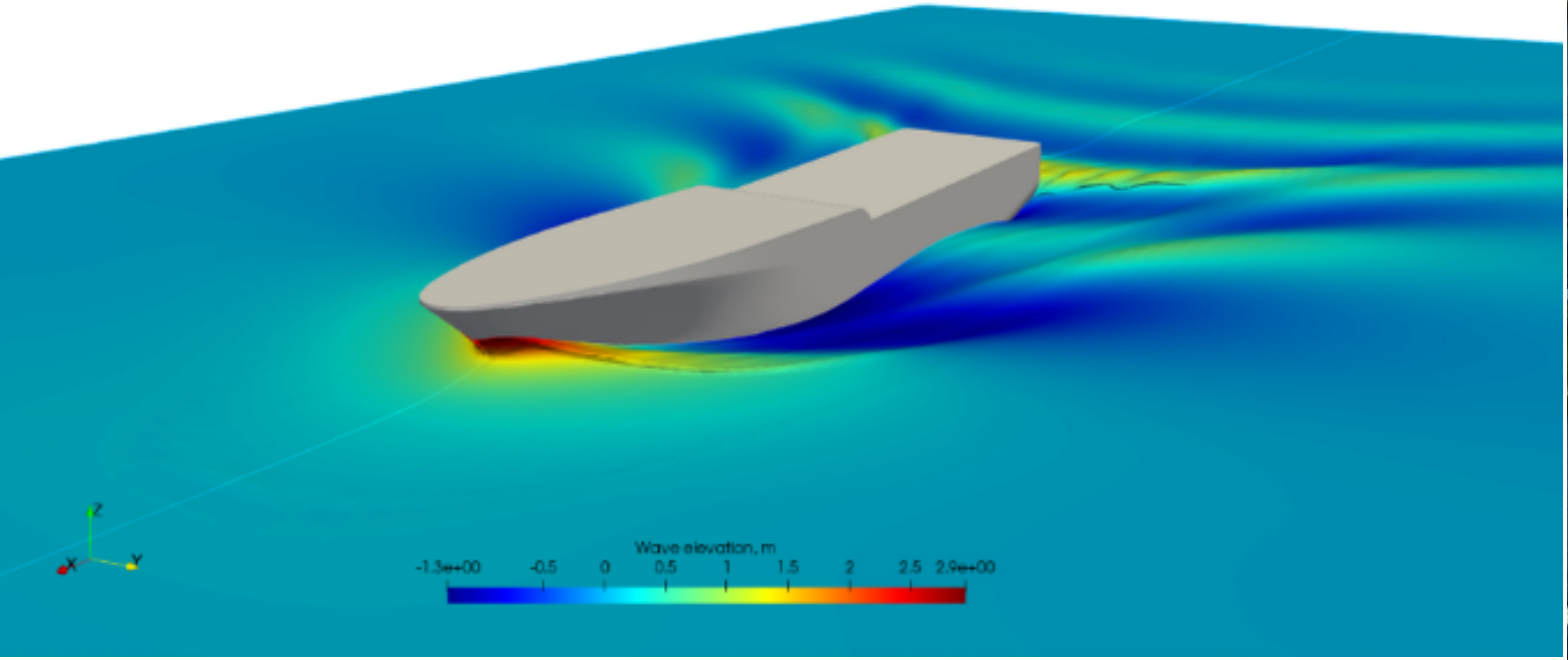


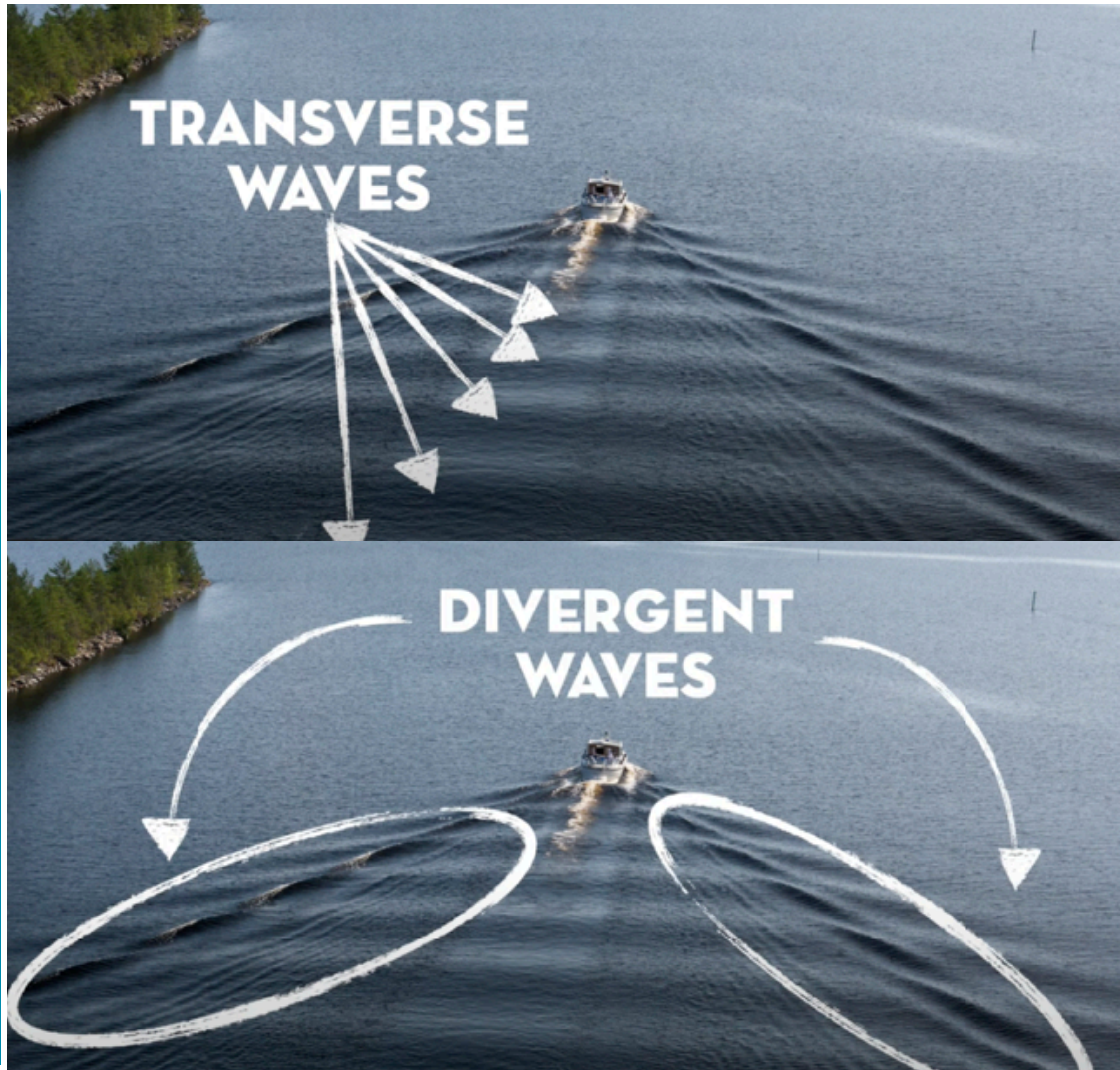



"THIS *$%£* BOAT CANNOT GO ANY FASTER THAN THIS"
WORLD MATCH RACING TOUR
CF 5467
2
5467 HH
3

HULL SPEED (DISPLACEMENT MODE)

Any hull going through the water creates two waves: One in front of the boat – the bow wash – and one at the stern – the wake. The faster a boat goes through the water, the bigger apparently the waves get. Until there is one point when the waves are too high and the trough is too deep so the hull is "trapped" in between two crests (and one truogh)– and cannot go any faster.



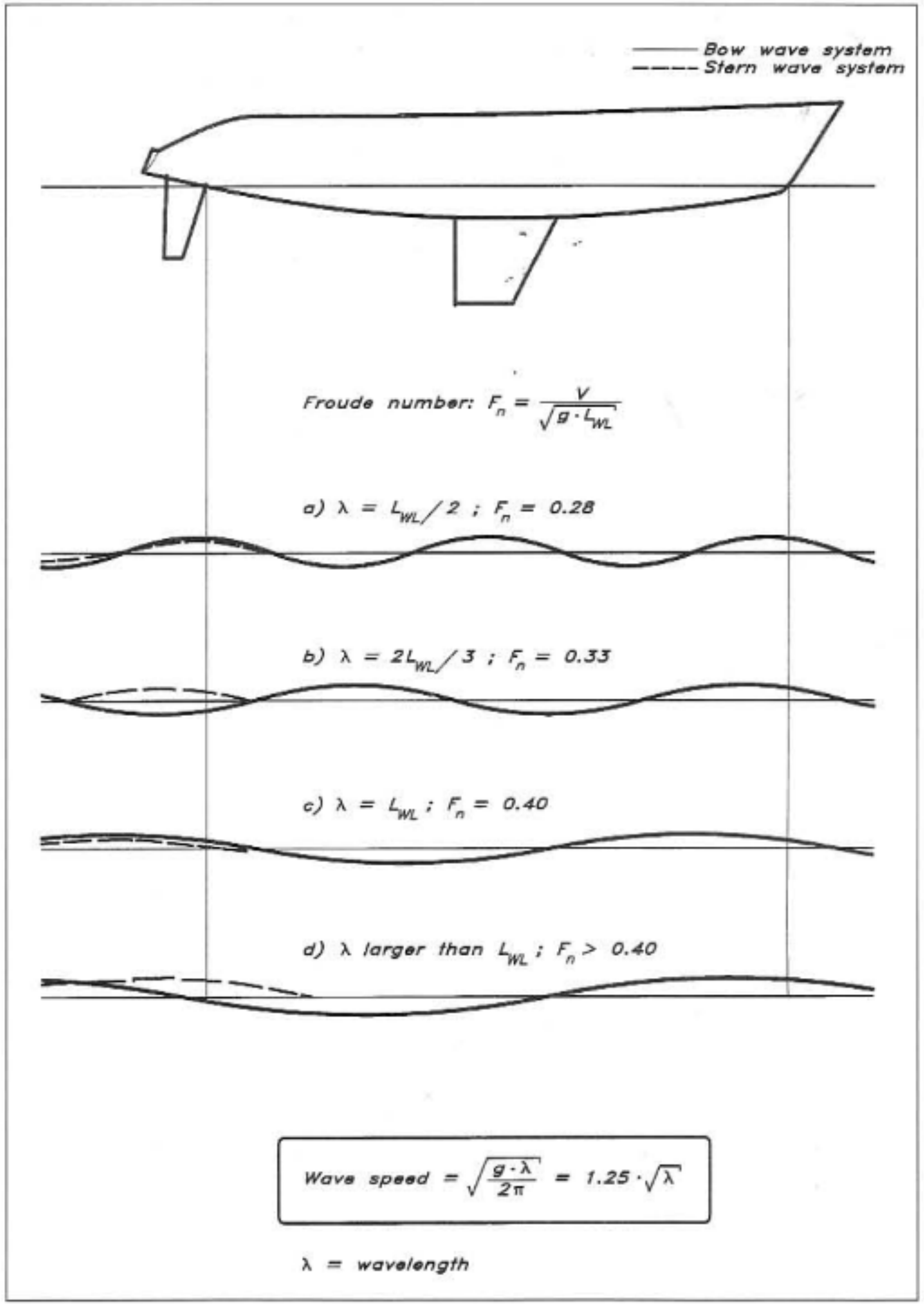


THE FIRST APPROXIMATION FOR HULL SPEED IS: HULL SPEED IS 1.34 TIMES THE SQUARE ROOT OF THE WATERLINE LENGTH OF YOUR YACHT.

FROUDE N: THE CRITICAL SPEED

The theoretical max hull speed is calculated through the Froude number, a ratio which is looking at the speed and the length of a body flowing through matter.

Froude number, which plays a similar role for the wave resistance as the Reynolds number does for viscous resistance vs inertia (to determine the type of flow pattern as laminar or turbulent). It is the Froude number that determines "how many waves there are along the hull".

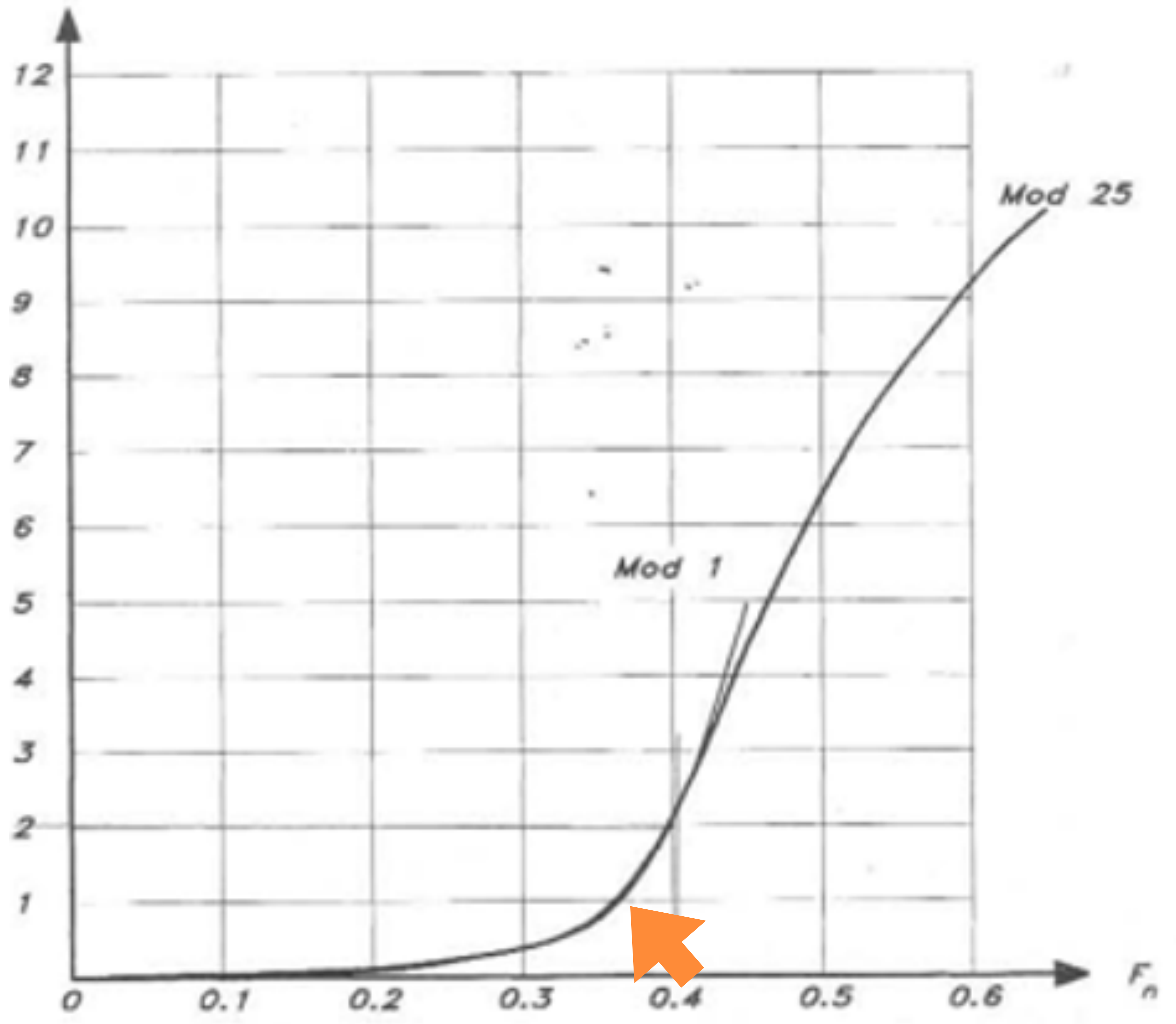


$$Fr = \frac{v}{\sqrt{gL}}$$

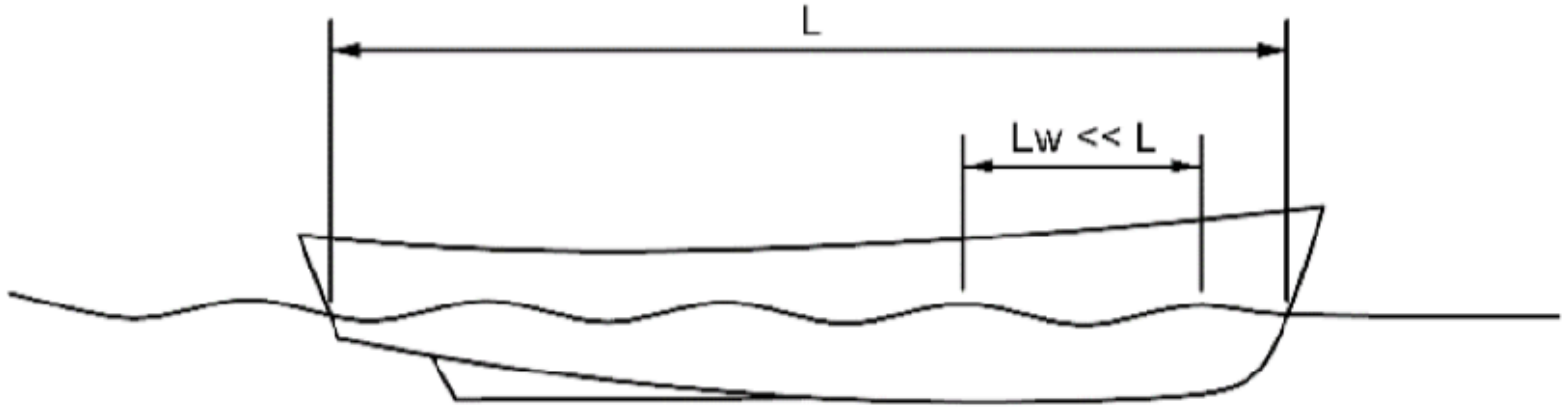
Flow velocity (the speed of the boat)

Wave velocity (depending by boat length)

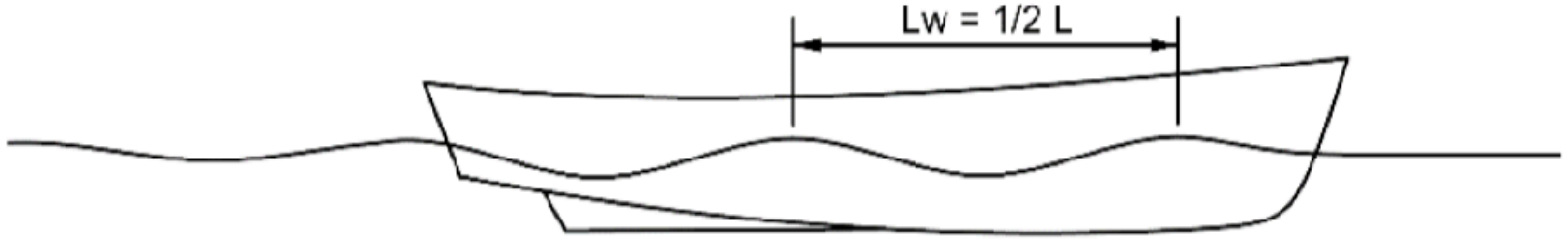
v = Velocity of the fluid flow
g = Acceleration due to gravity
L = Characteristic length



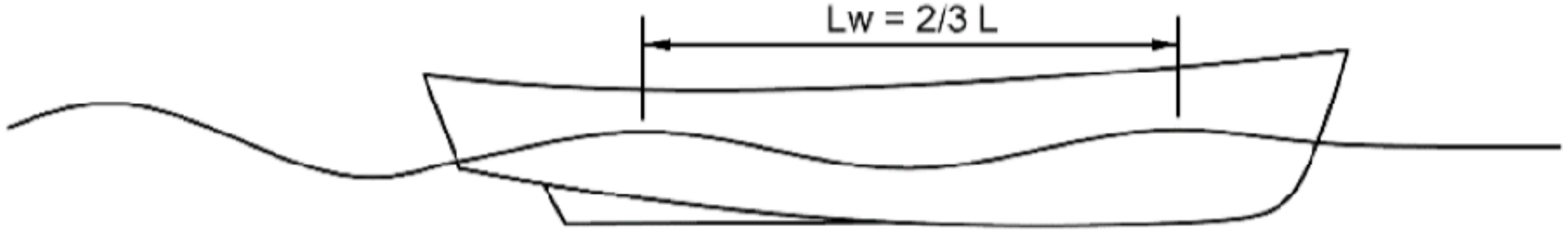
The largest hump in the resistance curve should occur when the wavelength is equal to the waterline length, at F = 0.40.



WAVELENGTH << SHIP LENGTH
SMALL WAVES SEEN ALONG SIDE OF HULL
MINIMAL WAVEMAKING RESISTANCE



Fn = 0.28
WAVELENGTH = 1/2 SHIP LENGTH
BOW WAVE SYSTEM HAS A CREST AT THE STERN
CREST PARTIALLY CANCELS STERN WAVE SYSTEM,
REDUCING WAVEMAKING



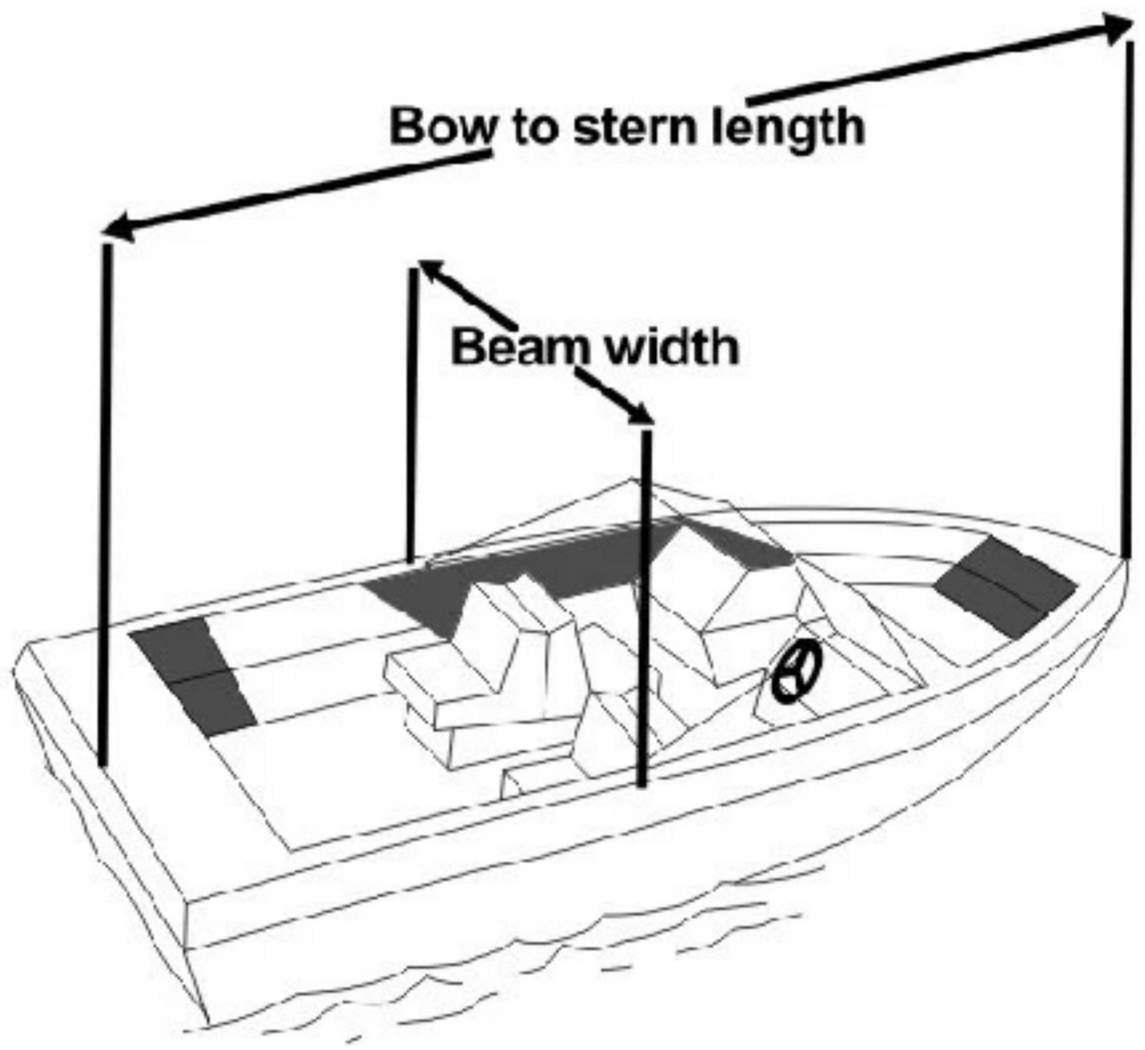
Fn = 0.33
WAVELENGTH = 2/3 SHIP LENGTH
BOW WAVE CREATES A TROUGH AT THE STERN,
WHICH ADDS TO THE STERN WAVE SYSTEM,
INCREASING WAVEMAKING

Fn = 0.40 or SPEED LENGTH RATIO = 1.34
WAVELENGTH = SHIP LENGTH
"HULL SPEED" LAST EFFICIENT SPEED
FOR DISPLACEMENT SHIPS

Fn = 0.5
WAVELENGTH = 1.5 SHIP LENGTH
"HUMP SPEED" - WORST SPEED TO OPERATE AT

THIN OR BULKY?

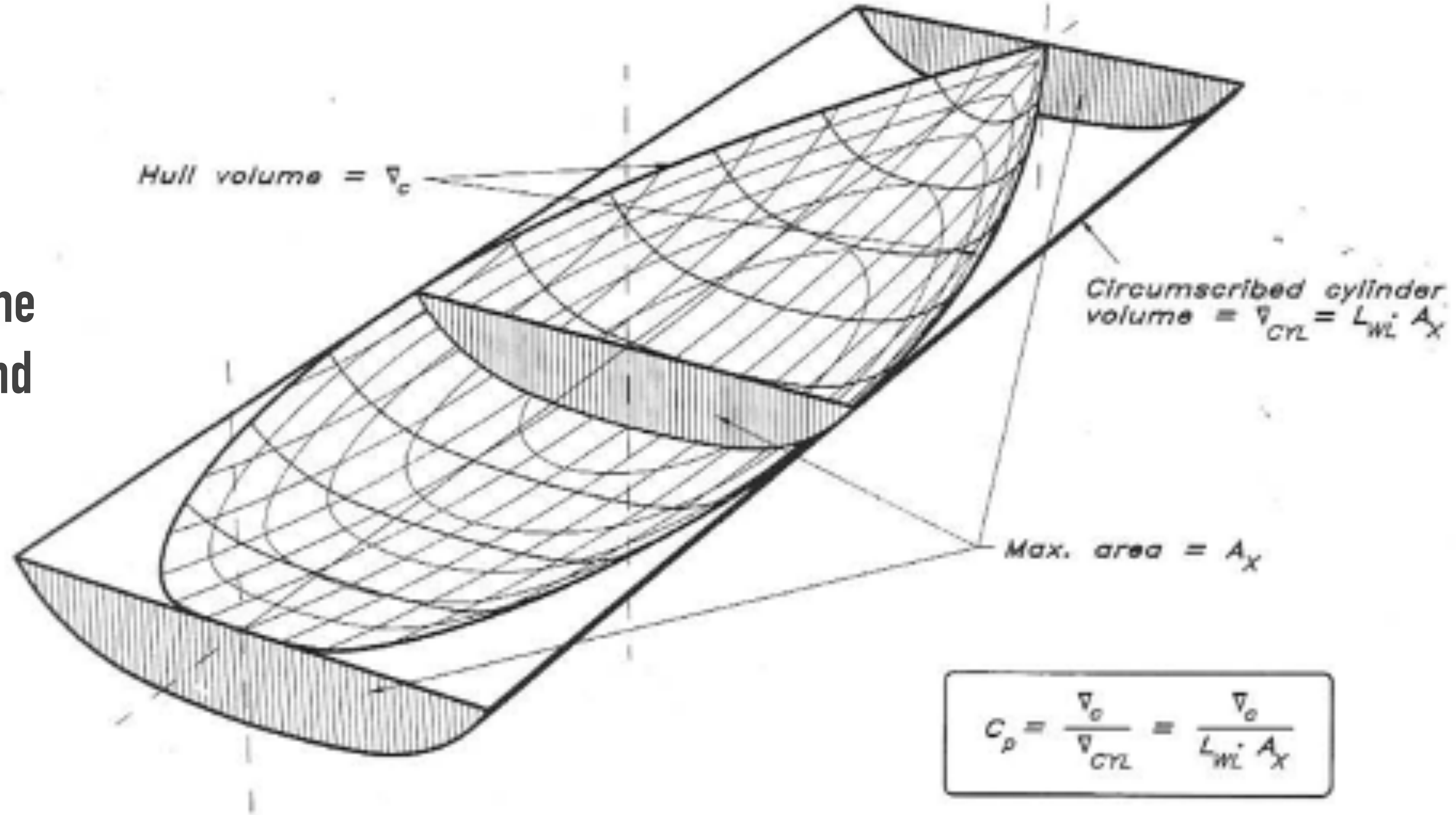
PRISMATIC COEFFICIENT



The beam is one of the governing factors in ensuring adequate stability. However, an increase in B will increase the resistance unless it is accompanied by a corresponding increasing in length.

The prismatic coefficient is defined as 'the ratio of the immersed volume to the volume of a prism with its length equal to the waterline length and cross-sectional area equal to the maximum cross-sectional area'.

The Cp thus indicates the longitudinal distribution of the underwater volume of a yacht's hull.



A low (fine) Cp indicates a hull with fine ends and less resistance and power requirements at low speeds.
However, she could be instable at higher speed

A large (full) Cp indicates a hull with relatively full ends.
It means more resistance and power requirements at low speeds, but also more stability for higher speeds.

Optimal Cp for a sailingboat around 0,56 (between 0,5 and 0,6) – lower than 0,5 is good for speed, higher than 0,6 is good for stability.

SAME SHAPE – DIFFERENT SIZE
SAME "PERFORMANCE-FAMILY"

Scaling factor Assuming scale factor = x

- Length (L) = L x
- Sail Area (As) = As $x^{1,85}$
- Beam (B) = B $x^{0,70}$
- Hull Volume (Vh) = Vh $x^{2,40}$
- Wetted area (Ah) = Ah $x^{1,63}$

*ATTENTION TO MINIATURIZE (ONBOARD HUMANS CANNOT BE SCALED. IN YOUR FISH, PROTOTYPE PROCESSES MATTER)

KEELS AND RUDDERS ARE CRITICAL HYDRODYNAMIC SURFACES THAT PROVIDE STABILITY, LIFT, AND MANOEUVRABILITY

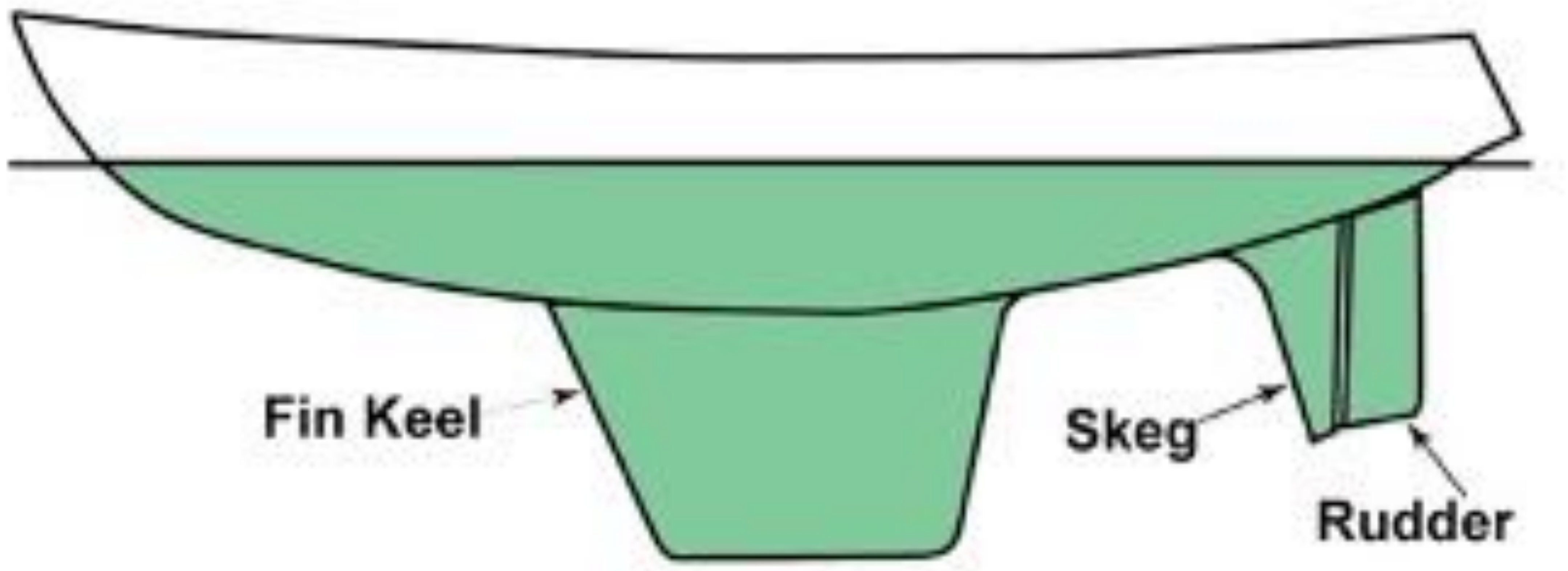

FOILS ARE DESIGNED TO LIFT THE HULL OUT OF THE WATER, DRASTICALLY REDUCING HYDRODYNAMIC DRAG

APPENDAGES DESIGN

CAUDAL FIN – PROPULSION (CONTRIBUTE IN ACCELERATION - SIMILAR EFFECT OF FOIL RUDDER)

DORSAL ANAL FIN – KEEL (FOR STABILITY)

PECTORAL FIN – RUDDER (CONTROL INCLINATION, LIFT AND STABILITY)

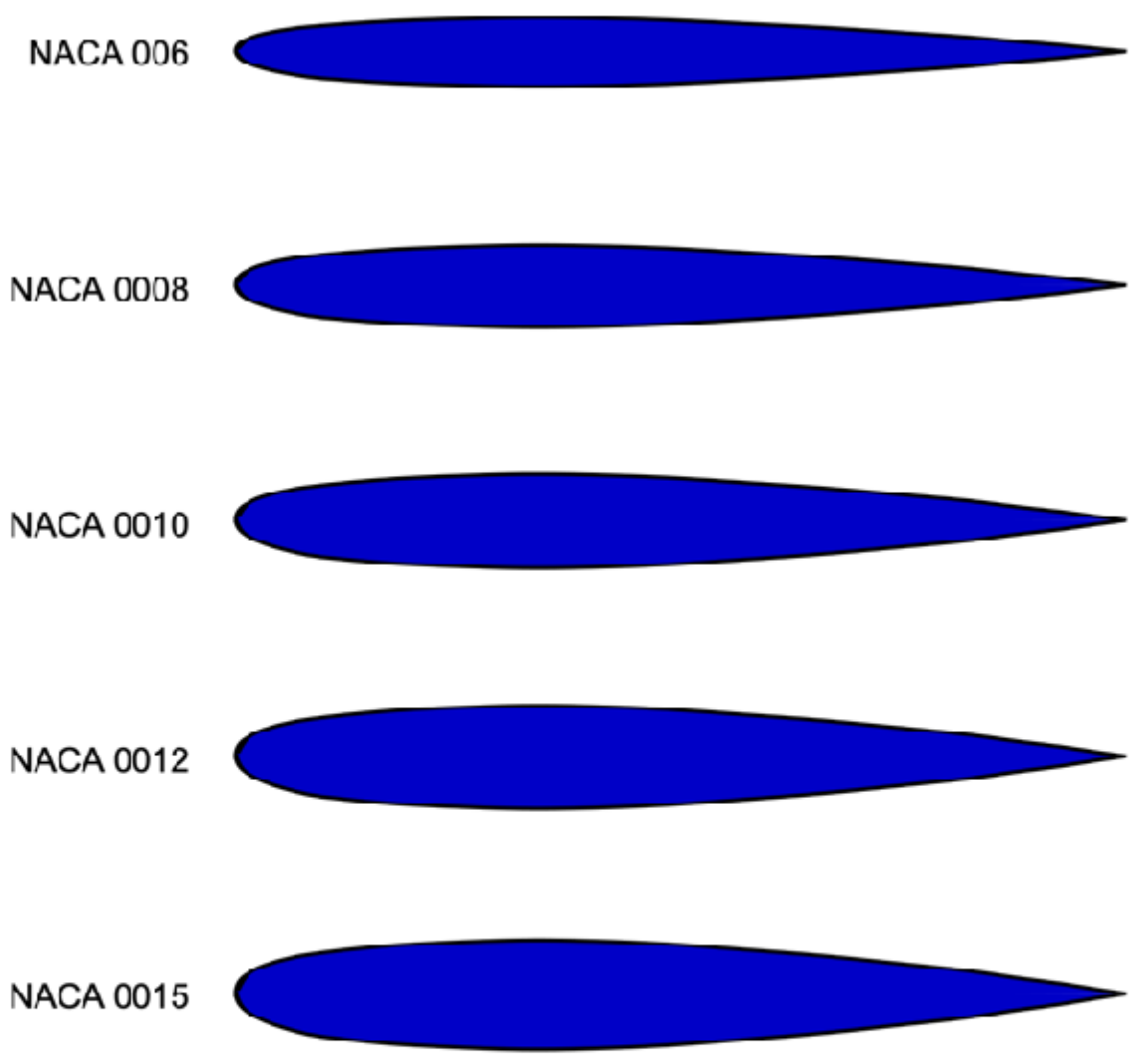


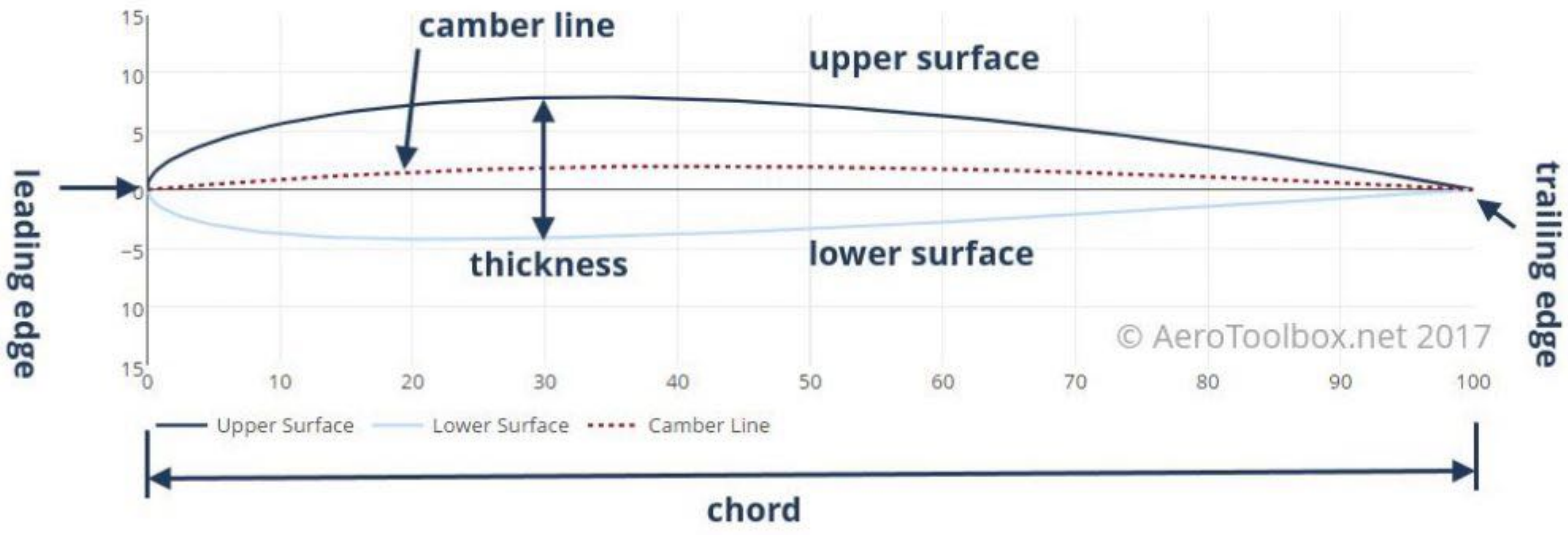
Traditional Sailboat keels and rudder has symmetric profiles.
When a wing works properly the water flow on both sides is attached.

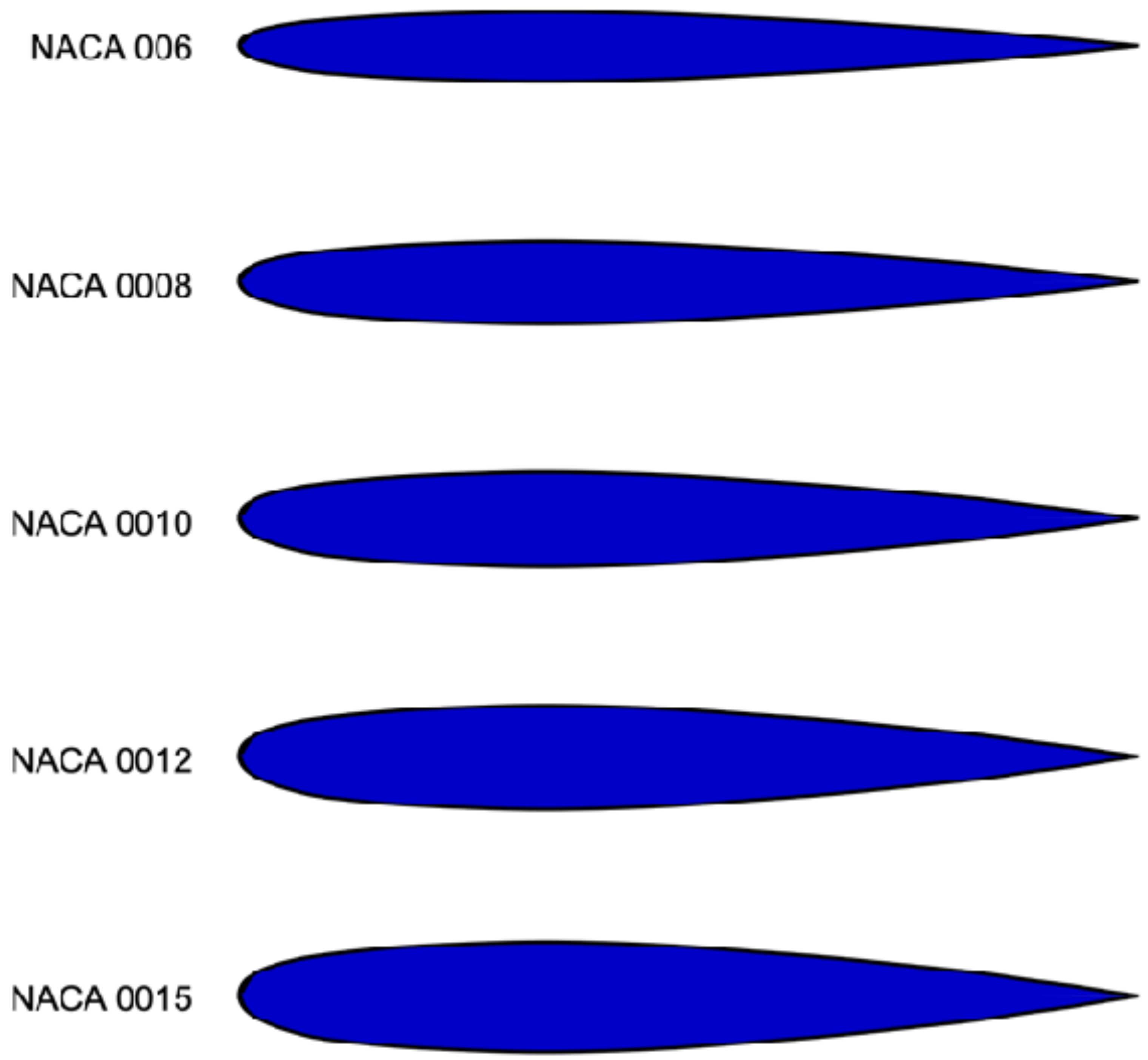
- Commonly shaped using NACA profiles for smooth, laminar flow
- Optimized for low drag
- Help maintain stability

NACA PROFILES

NACA profiles (developed by the U.S. National Advisory Committee for Aeronautics, the predecessor of NASA) are specific shapes used for airfoils (or hydrofoils), defined by a set of numbers (e.g. NACA 0012). They describe the shape of a foil (cross-sectional shape) that's optimized for efficient movement through a fluid, air or water.







The 4-digit NACA code format is: NACA [M][P][TT]

M = Maximum camber (% of chord)

P = Position of max camber (10% of chord)

TT = Maximum thickness (% of chord)

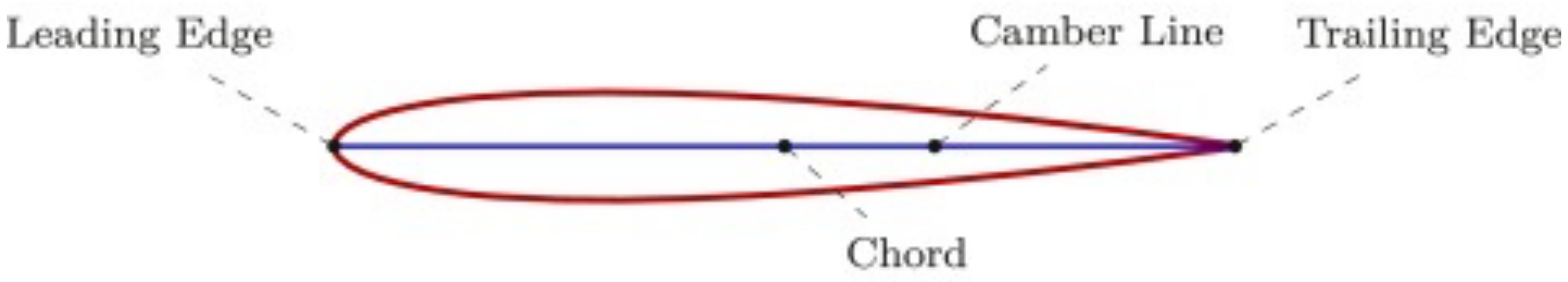
NACA 0012 (typically used in sailing boat rudders)

M = 0 - no camber (symmetrical)

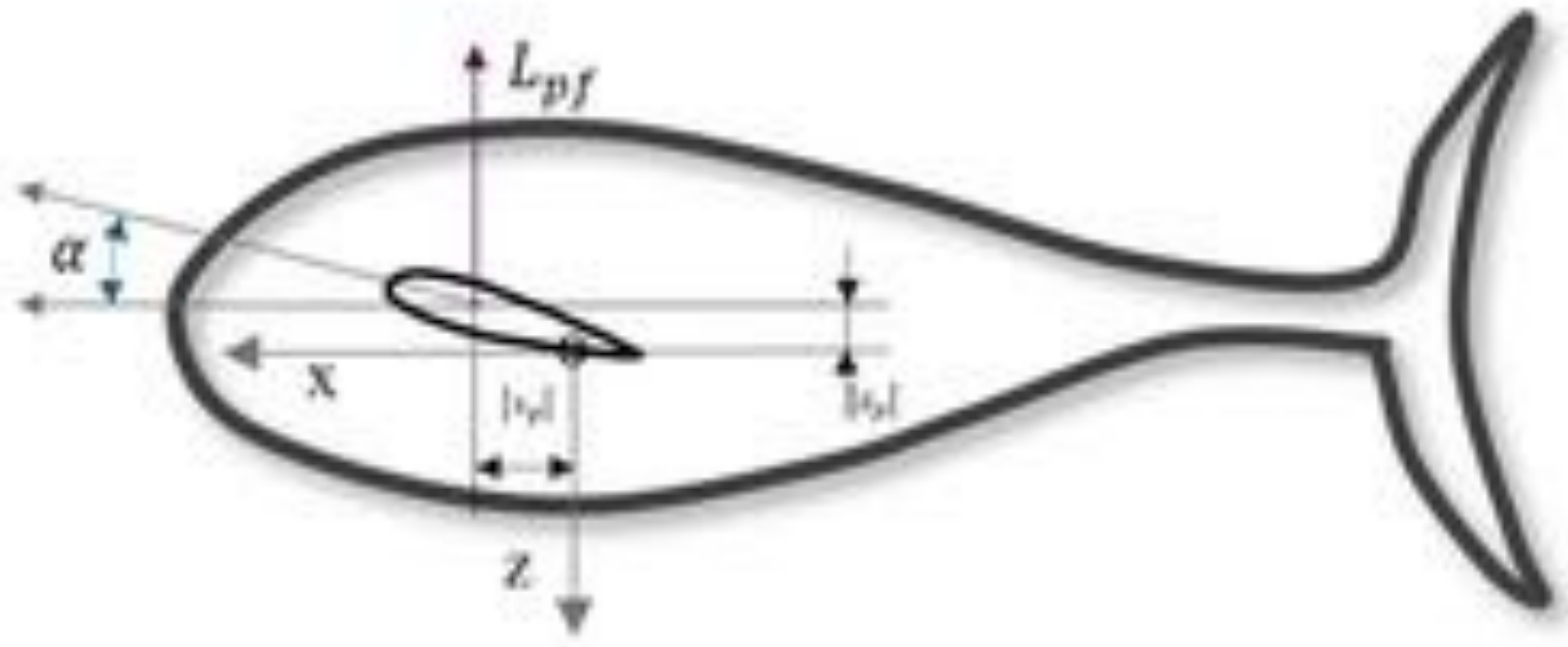
P = 0 - no meaning (no camber)

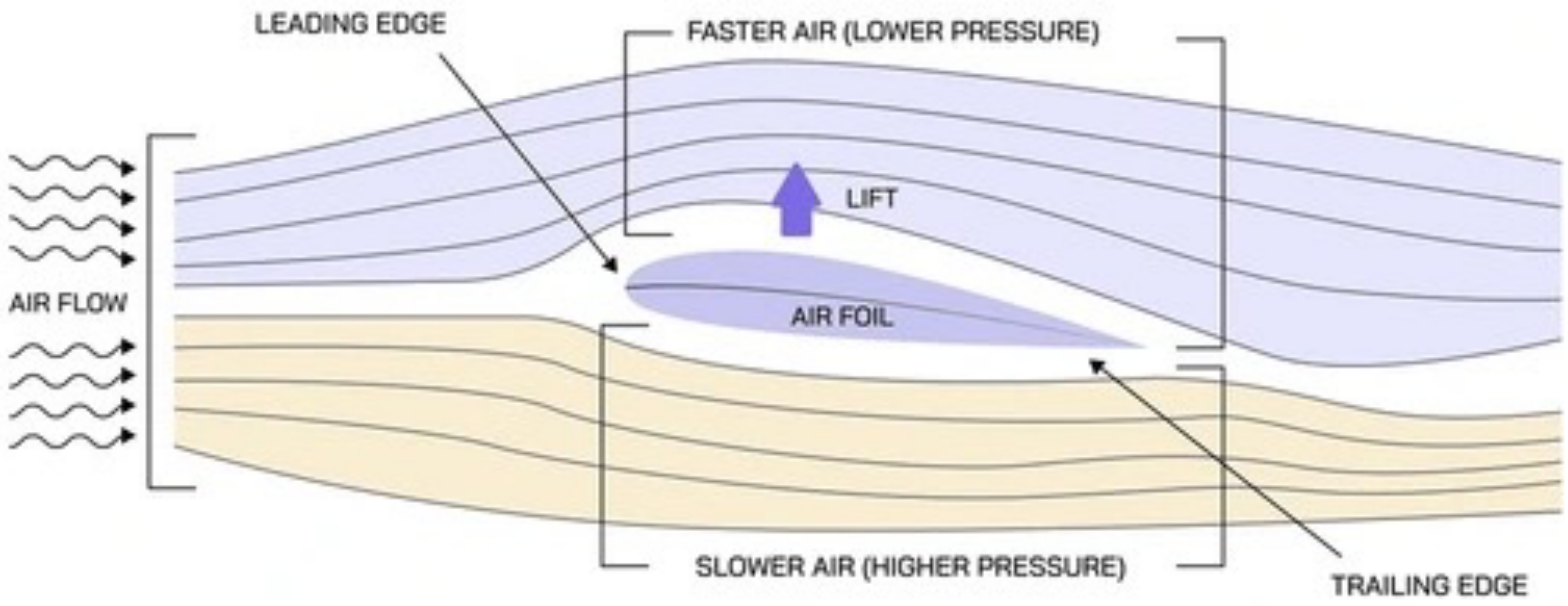
TT = 12% (for a 1-meter foil, the thickest point is 12 cm)

SYMMETRIC FOILS

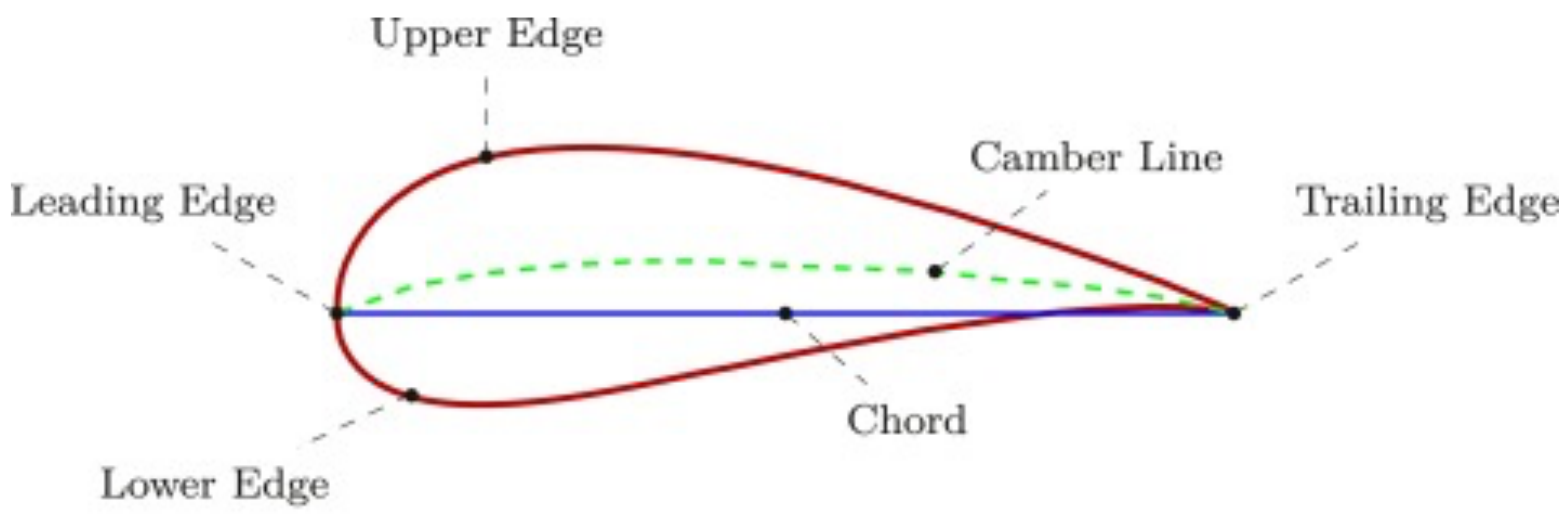


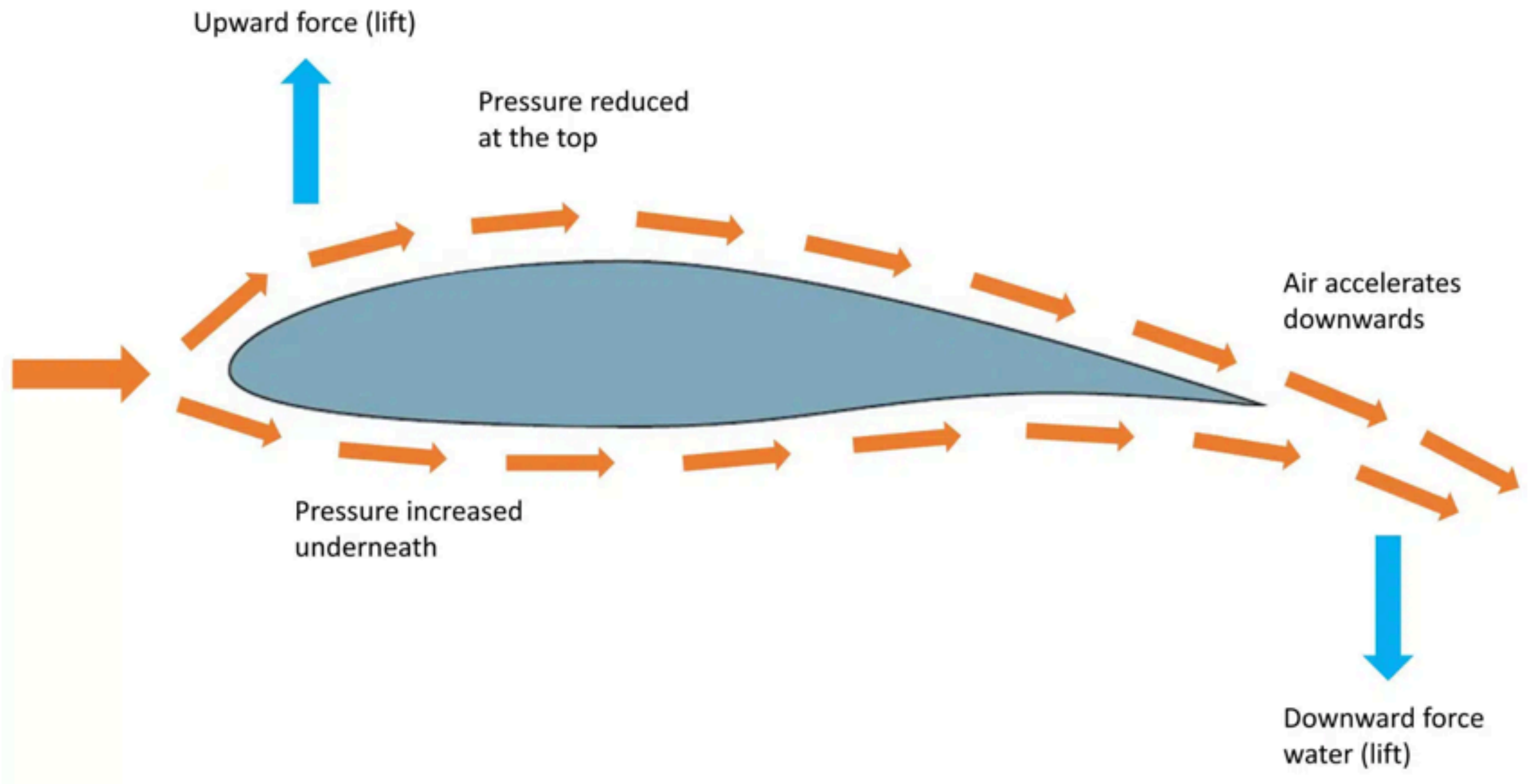
A symmetric foil has identical curvature on both its upper and lower surfaces. This means its shape is mirrored along the horizontal centerline (the chord). Because of this symmetry, it produces no lift when aligned directly with the flow (i.e., at 0° angle of attack). However, it begins to generate lift when the angle of attack increases (for example when a boat is sailing under sails)



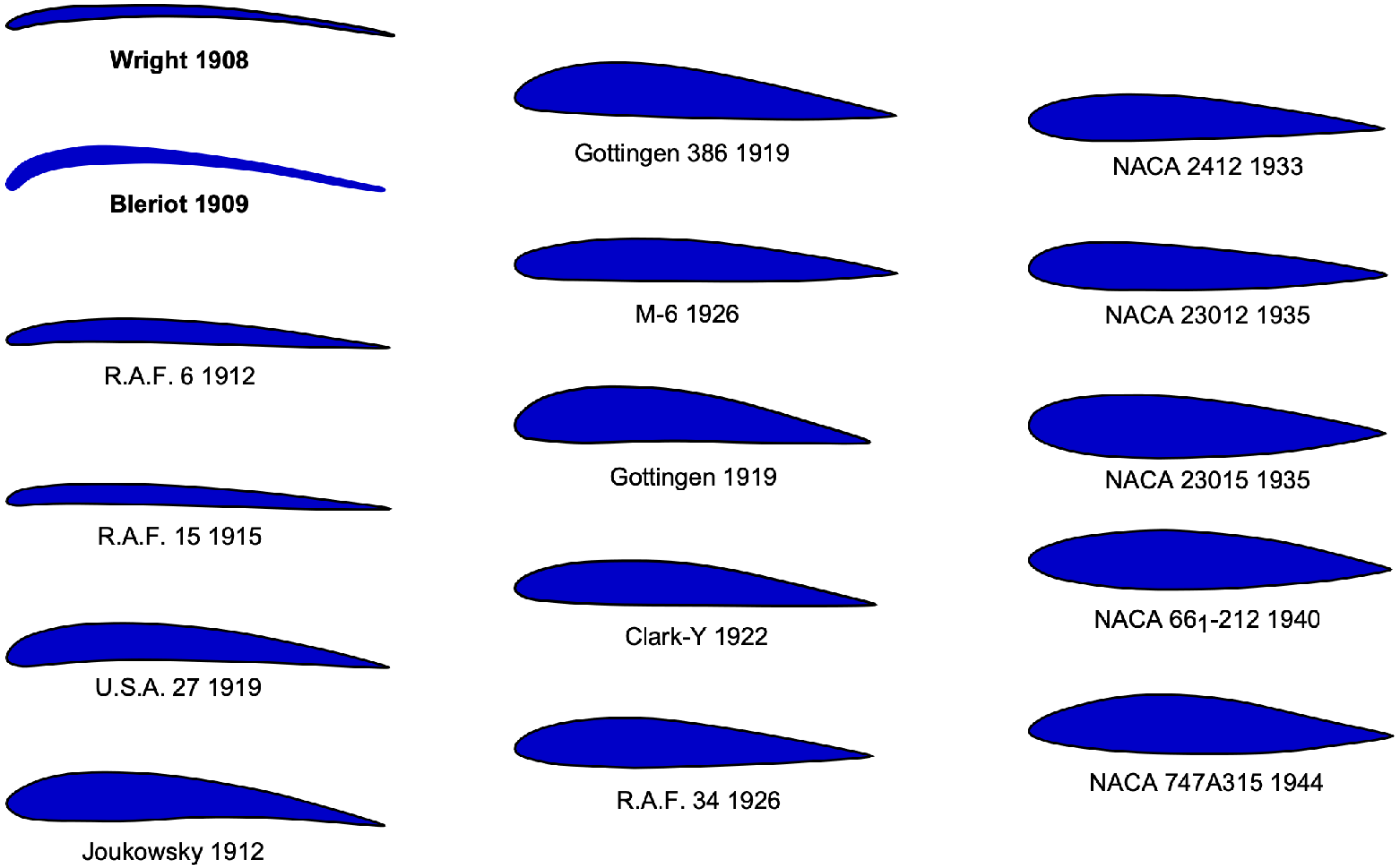


ASYMMETRIC FOILS



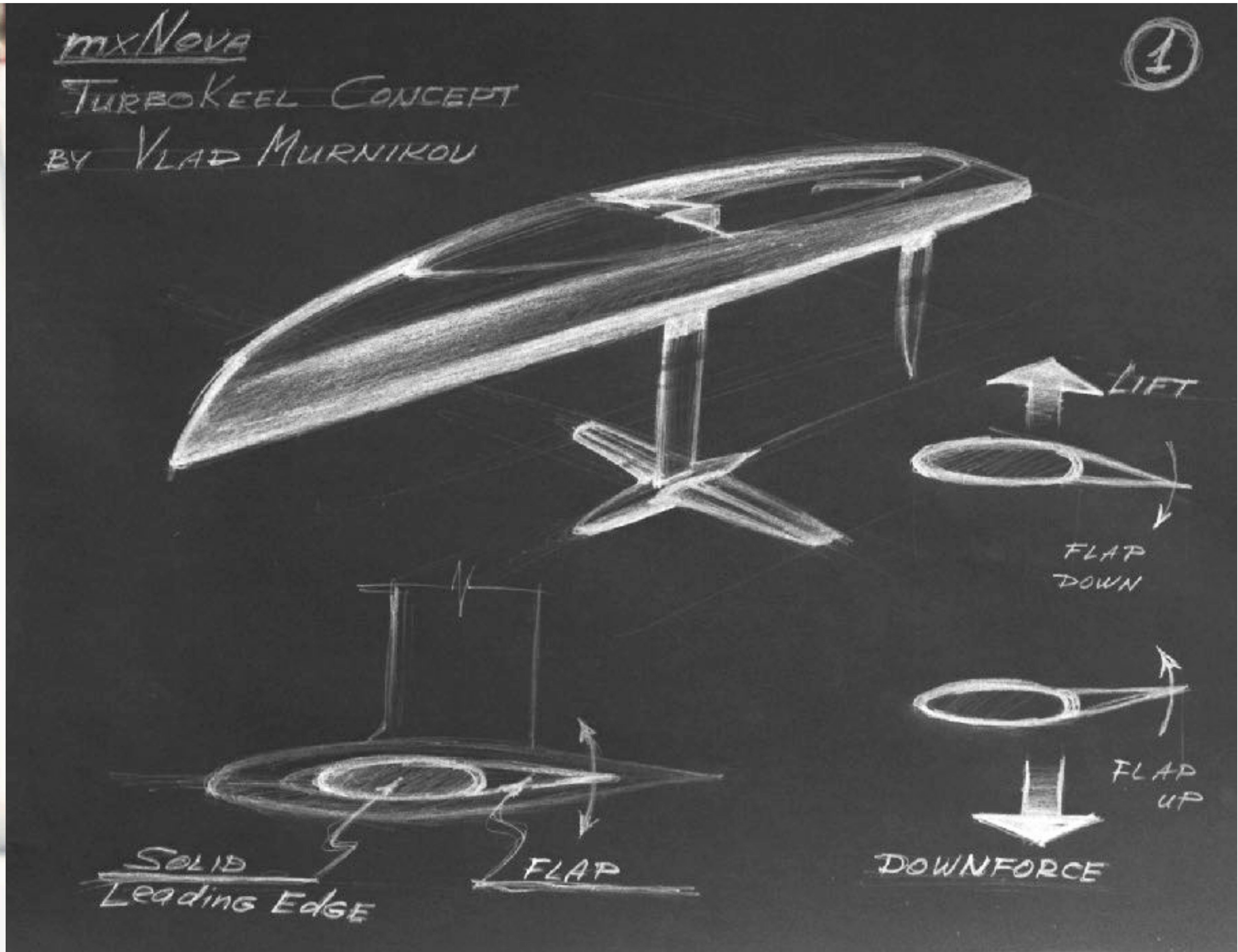


An asymmetric foil, or cambered foil, has a curved upper surface and a flatter lower surface (or vice versa). This shape causes the flow to move faster over one side than the other, creating lift even at small or zero angles of attack. The camber is typically positioned to favor one direction of flow. The camber helps reduce leeway (sideways slip) and increases efficiency. In nature, pectoral fins or flippers often have an asymmetric shape to provide lift or directional control, especially in animals like dolphins or flying fish.

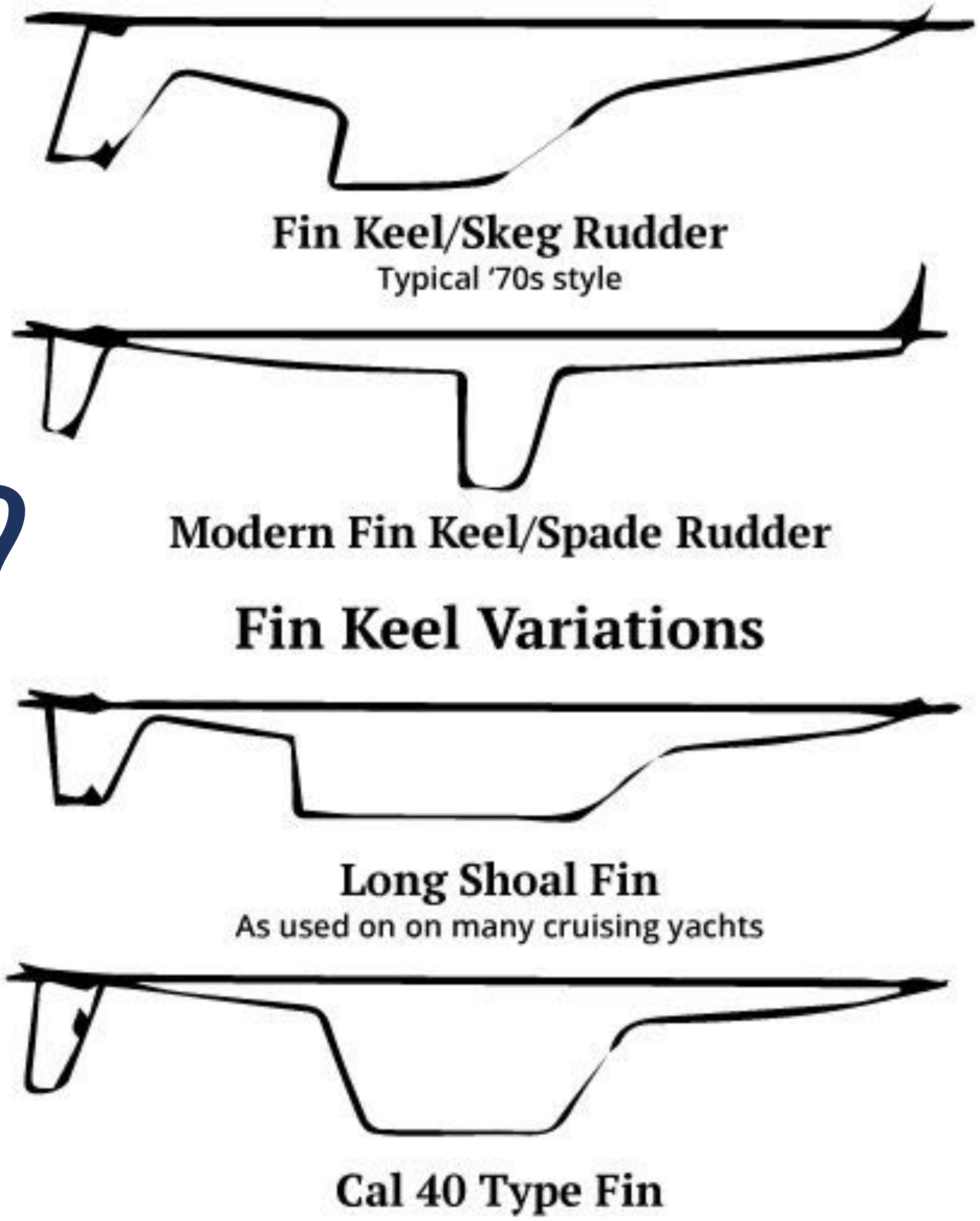

Wright 1908
Bleriot 1909
R.A.F. 6 1912
R.A.F. 15 1915
U.S.A. 27 1919
Joukowsky 1912
Gottingen 386 1919
M-6 1926
Gottingen 1919
Clark-Y 1922
R.A.F. 34 1926
NACA 2412 1933
NACA 23012 1935
NACA 23015 1935
NACA 66_1-212 1940
NACA 747A315 1944

FOIL TRIM

Sailingboat foils adjust their angle (modifying the camber) to control lift and keep the sailing boat flying stable above the water (like Wing flaps on aircraft extend or deflect to increase camber, boosting lift at lower speeds for takeoff and landing).



THIN OR BULKY?



Fin Design: Aspetc Ratio

Aspect Ratio is the ratio of a wing's length to its chord. Boats with higher maximum speeds are more apt to use high aspect ratio foils while slower boats are more suited to lower aspect ratio foils. A higher aspect ratio wing has a lower drag and a slightly higher lift than a lower aspect ratio wing (with same wetted surface).

SO WHY CHOOSING A LOW ASPECT RATIO?

STRUCTURE

The longer your wing is, the stronger it needs to be; water load is placed across the entire span, which creates more of a bending moment.

WEIGHT

The longer it is, the more it tends to bend. To overcome the bending, you need a stronger wing, which means you need more material. And when you add more material to the wing, it becomes heavier

MANUFACTURE

The longer and thiner fin is, the most difficult is to prototype it

PRACTICAL

Longer fins/reel means less manoeuvrability space (and risk to bump something/somewhere). Low AR foils are generally more stable (and act as stabiliser)

SAME (NACA) PROFILE – DIFFERENT SIZE
SAME "PERFORMANCE-FAMILY"

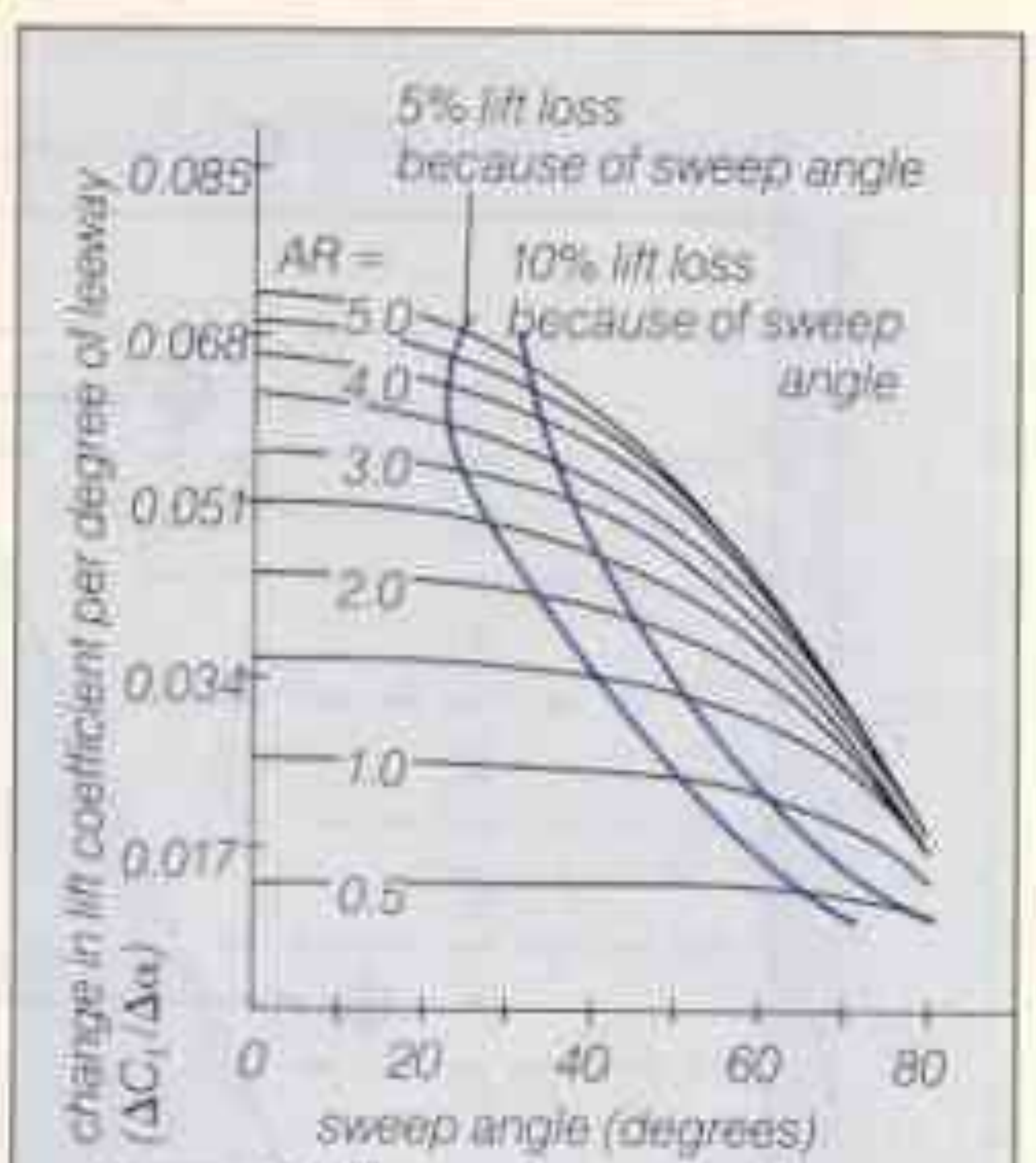
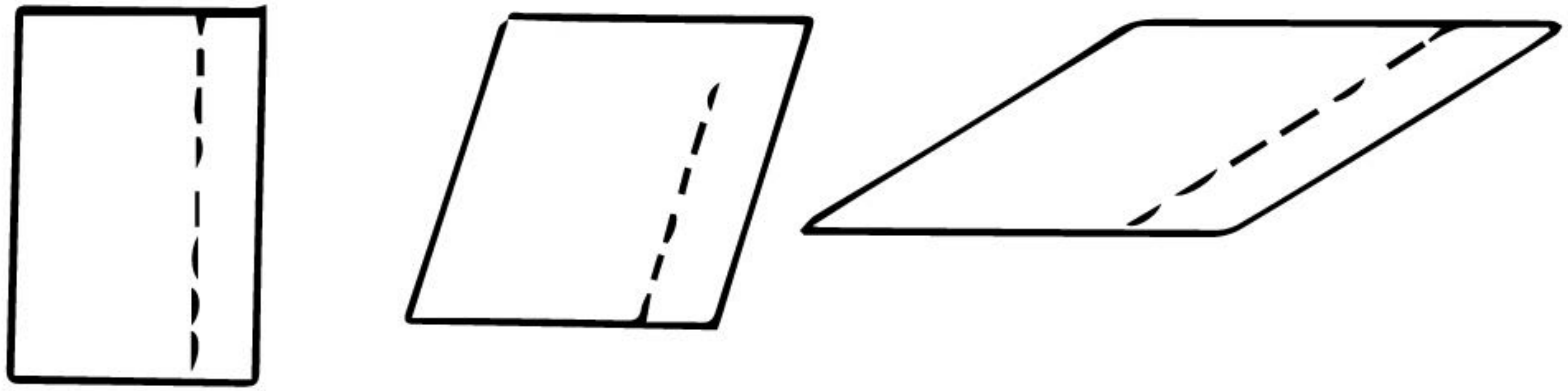


Figure 1: Effects of aspect ratio and sweep angle on the lift curve. Note that as aspect ratio increases, the lift available per degree of leeway also increases

Tank tests showed that highest efficiency and lowest drag were achieved when low-aspect-ratio keels were highly swept back and high-aspect ratio keels were left unswept. A designer may still choose a sweep angle because he believes it will shed kelp or to achieve a particular location for the center of gravity, however.



AR = 1.5
Sweepback = .5°

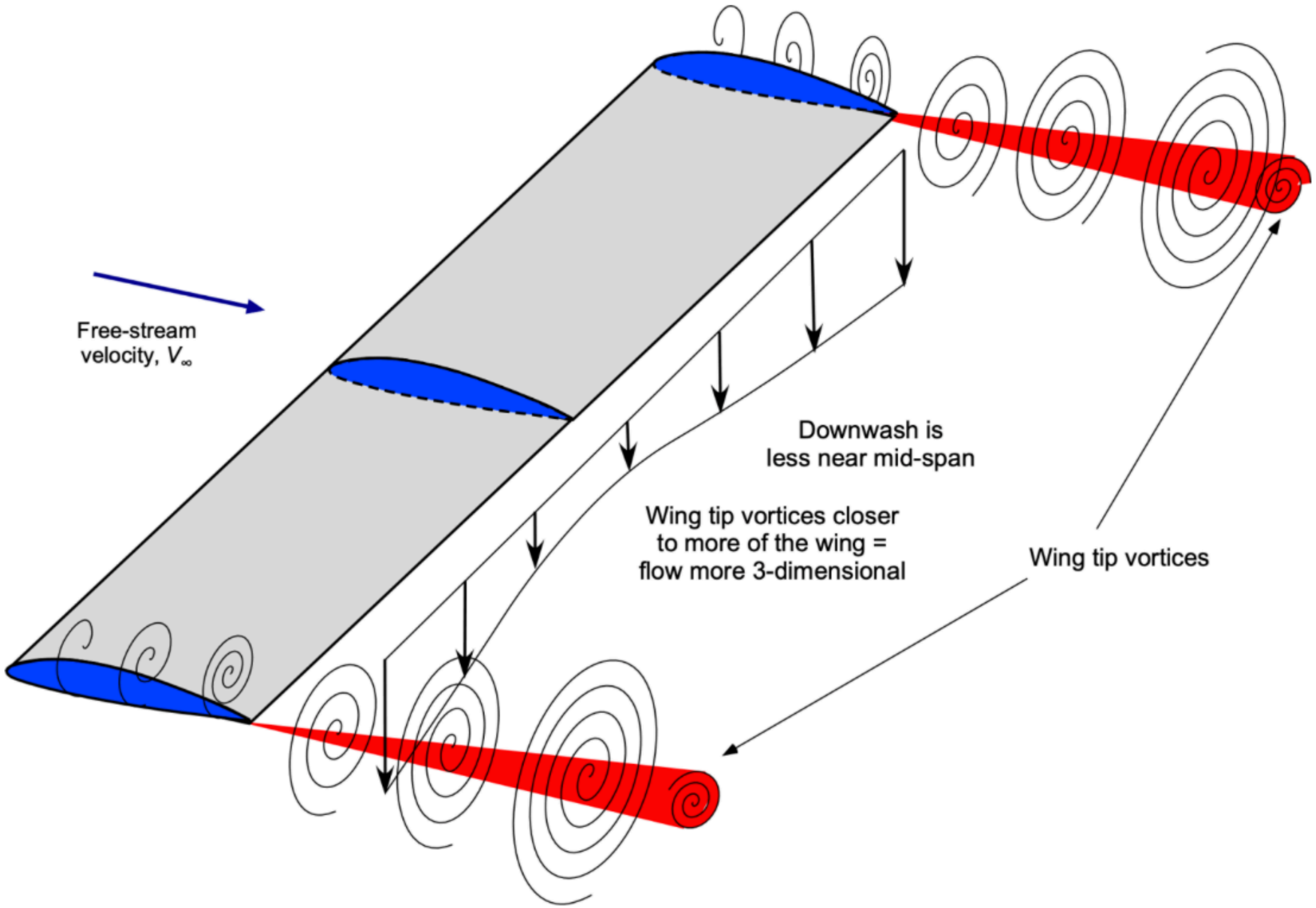
AR = 1.0
Sweepback = 16.5°

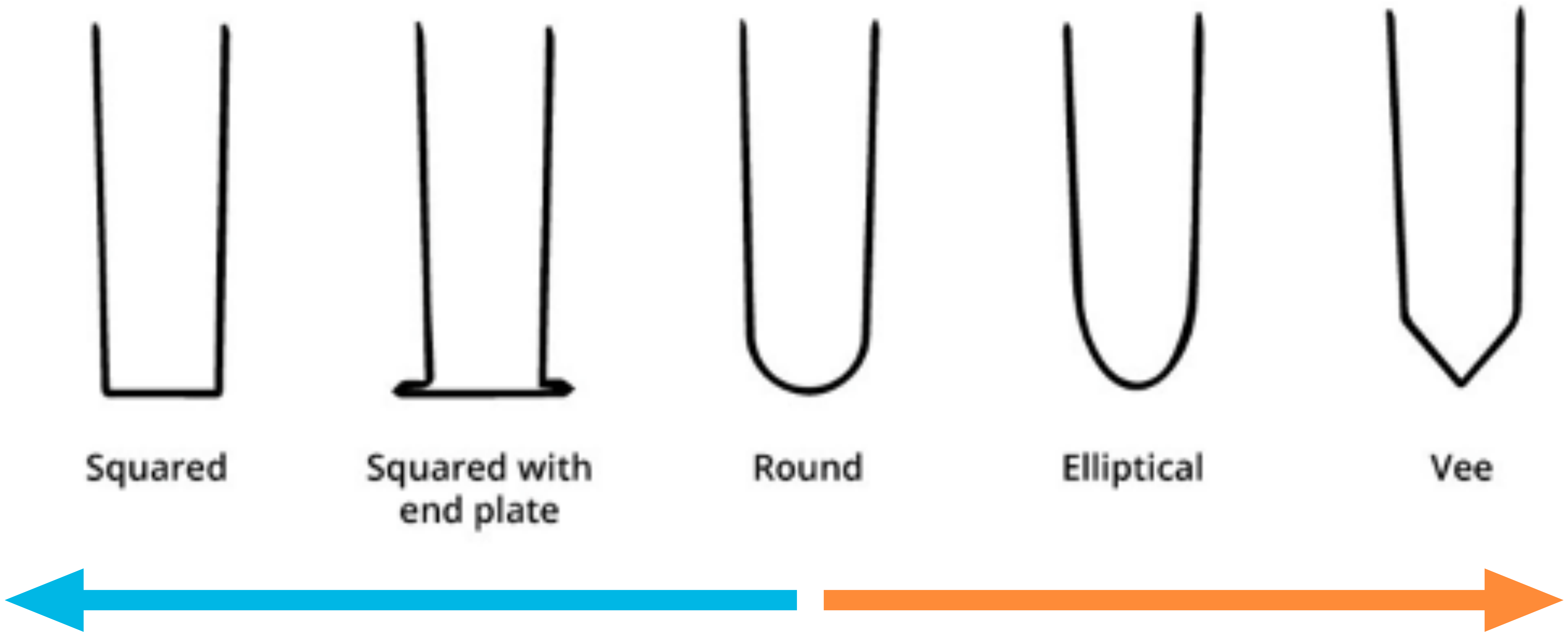
AR = .5
Sweepback = 58°

TIPS MATTER

At the tip of a foil, high-pressure water from below tries to "escape" to the low-pressure side above. This causes swirling flow called a tip vortex, inducing drag.

Tests show that the flat, squared-off tip develops a bit more lift to windward and that the round or elliptical tip has less drag on a run.





MORE LIFT
MORE STABILITY
MORE TIP VORTEX
MORE DRAG

LESS LIFT
LESS STABILITY
LESS TO 0 TIP VORTEX
LESS DRAG

HOW TO CREATE A WINNING DESIGN?

THINK HOLISTICALLY!

- A yacht doesn't win because one part is perfect. It wins because the system works as a whole
- Every design decision affects others
- Winning is about integration, iteration, and intentional trade-offs
- Balancing constraints and exploiting the rules

FAIL EARLY
FAIL OFTEN
BUT ALWAYS FAIL FORWARD

- The team with the most water pre-tests wins
- You need to go through a lot of component failure before reaching an optimal design
- Better to simplify… prototyping process could affect quality
- Learn from others (also other mistakes)