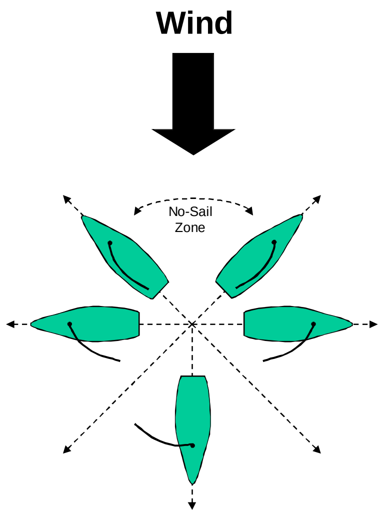
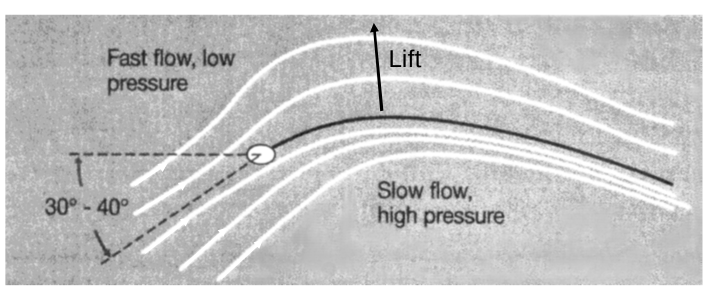
Which Wind Directions Can Be Sailed, and How?



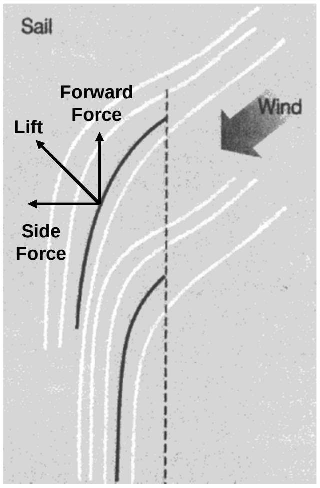
- It's easy to understand sailing downwind (*resistance to the wind*)
- Sailing perpendicular to the wind is certainly possible, but perhaps less obvious
- What about sailing upwind?
  - Upwind sailing is possible because of *aerodynamics and hydrodynamics ("Lift")*
  - Same principals that allow airplanes to fly
  - No sailing in the "*No-Sail Zone*" (roughly 45 degrees off of the wind in each direction)
- Sailing directions between upwind and downwind use a blend of aerodynamics and resistance to the wind

The Sail as an Airfoil ("Wing")

- Air flowing over top of "wing" develops low pressure and "*Lift*" (*Bernoulli's Principle*)
- Lift (and "Drag") depends on *airfoil shape* and "*angle of attack*"
  - Object is to develop smooth flow, no turbulence, and to maximize Lift and minimize Drag
  - With a sail as an airfoil 30-40^{o} are required
  - Too much angle leads to too much Drag and little Lift
  - To little angle leads to "*Luffing*", and no Lift

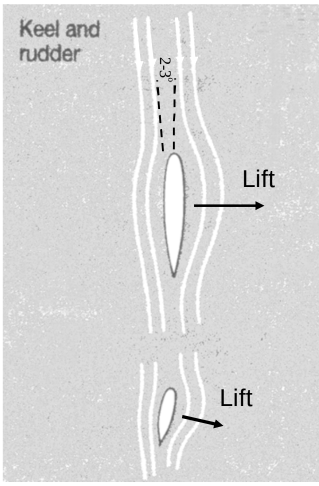


Forces Generated by Sails



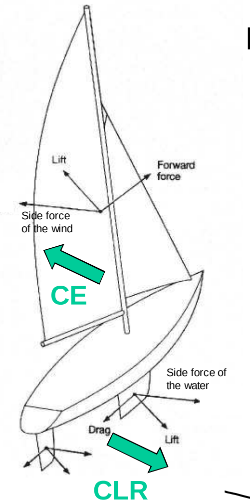
- When sails are trimmed properly for upwind sailing a strong Lift force is generated
  - The Lift force points forward
  - It provides the driving force for the sail (and boat)
  - It also pushes the sail (and boat) sideways
- If the wind is coming too much from the front, there won't be any airfoil shape, and no Lift (Luffing)
- If the wind is coming more from the side, you can let the sail further out
  - Keeps the airfoil shape
  - The Lift force still points forward
  - Very fast sailing

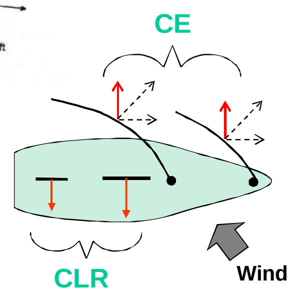
Keel and Rudder as Hydrofoils



- The Keel (also centerboards, etc.) and the rudder are both "***hydrofoils***"
- ***They resist sideways motion***
- If properly oriented, they also develop "***Lift***" (and Drag) which ***pulls*** the boat sideways
  - Very important for counteracting the sideways force of the wind
  - Boat sails fastest when the hydrofoils also have an ***angle of attack,*** with respect to the water flow (only 2-3^{o})
- Boat designers create this angle of attack by building in a slight ***Weather helm*** (tendency to turn into the wind); rudder has to be turned slightly to keep the boat on course.

Forces on the Boat - Overview

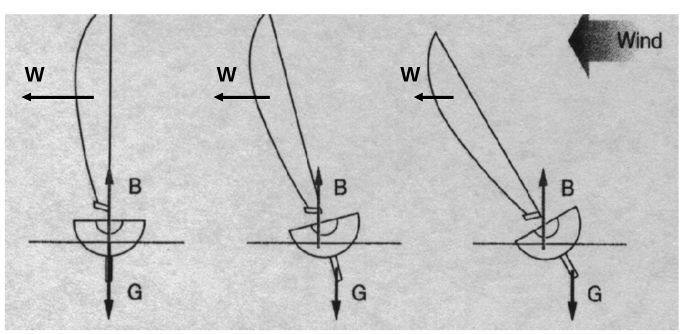




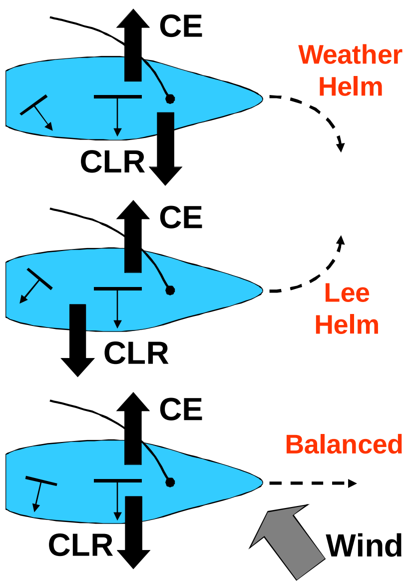
- **Sails (main and jib) provide Lift (forward force and *sideways* force)**
- **Position of sum of these sideway wind forces is *"Center of Effort" (CE)***
- **Keel and rudder provide resistance and Lift (sideways force and Drag)**
- **Position of sum of these sideways underwater forces is *"Center of Lateral Resistance" (CLR)***
  - ***Greatly influenced by rudder***
- **Balance**
  - **Boat accelerates until *forward force = Drag***
  - **Boat sideways slippage is reduced by *CLR balancing CE***
  - **Boat turns one way or the other until CE position is balanced by CLR position**

Forces on the Boat - Heeling

- **Wind force (W) tries to tilt the boat over (*"Heeling"*)**
- **Force at *Center of Buoyancy* (B) acts as fulcrum**
- **Force at *Center of Gravity (CoG)* pulls down (G), and resists Heeling**
- **Balance of Forces stops heeling**
  - **Wind force decreases as boat heels**
  - **Gravity force has more leverage as boat Heels**
  - **Leaning out to windward (*"Hiking"*) moves CoG ⇒ more leverage**

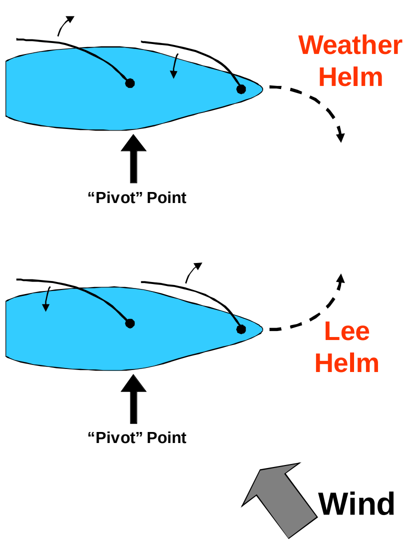


Forces on the Boat - Turning



- "*Weather Helm*" is the tendency for the boat to turn toward wind
  - CE behind CLR causes twist
  - Most boats are built with a little natural Weather Helm
  - For safety: boat stops sailing if no steering is applied
  - Also caused by rudder, Heeling
- "*Lee Helm*" is the tendency to turn away from wind
  - CE in front of CLR causes twist
- Various factors effect type of "Helm", including sail trim, angle of mast, etc.
- Balanced CE & CLR stops turning
  - Slight turn away from wind shifts CLR to correct natural Weather Helm

Balance – How to Achieve It



- If you have to turn the tiller or wheel too much to keep the boat sailing straight, you have too much "helm"
  - Too much tiller or wheel slows the boat down (*bad*)
- To reduce *Weather* helm, let out mainsail and/or trim in the jib
  - Make small adjustments and note whether wheel/tiller can be straightened more
  - Try to keep each sail optimally trimmed for maximum propulsion
- To reduce *Lee* helm, let out jib and/or trim in the mainsail
  - Make small adjustments and note whether wheel/tiller can be straightened more
  - Try to keep each sail optimally trimmed for maximum propulsion