edges. Boats rely on the flow of the wind, relatively slow compared to the much faster airflow generated by an engine-powered aircraft. They are severely limited in the amount of energy they can exploit. When resources are scarce, skills are challenged even more. Being able to change the sail's shape and the angle at which air flows over it to suit varying wind strengths and directions is critical to extract the required lift from the available wind energy and to minimize the inevitable drag.

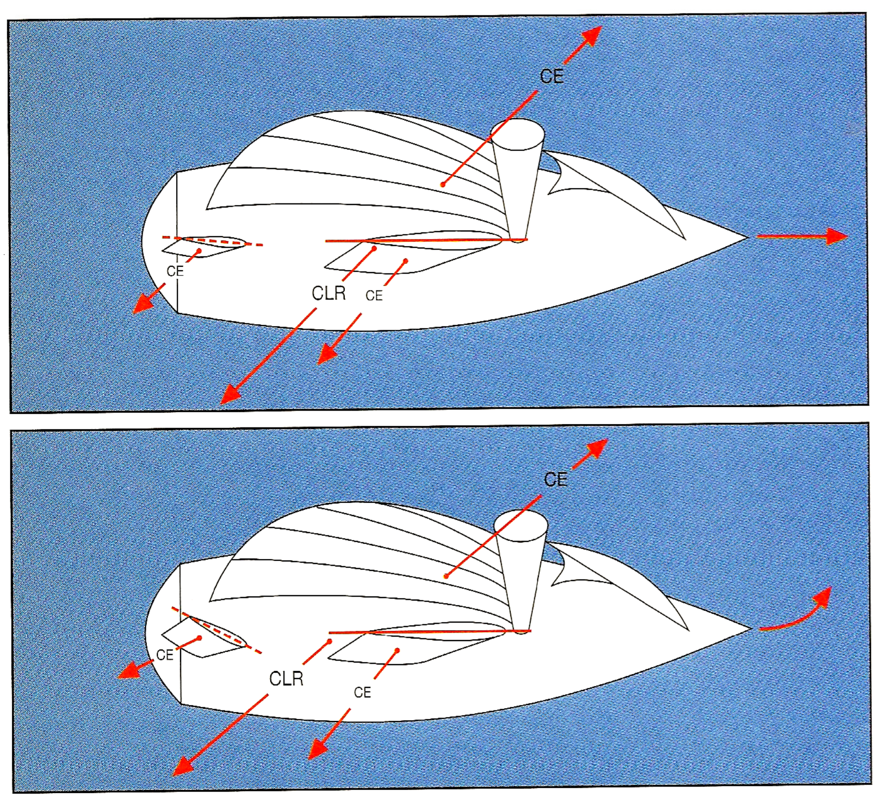
If there is no corresponding hydrofoil already at work, the result of this careful sail trimming is just unresisted sideways motion, resulting in slower airflow, resulting in less speed—in other words the boat slides aimlessly. You have probably seen this happen when a sailing dinghy leaves the wharf with its centerboard up.

The addition of underwater fins—a keel or centerboard and a rudder—vastly increases lateral resistance. Again, unlike most airplane wings, a sailboat's foils are symmetrical (because they have to work the same way on both sides). Hydrofoils, like sails, also have to meet the oncoming flow at an angle, called an angle of attack, before they develop any lift. Since most keels are rigidly attached to their hulls, the whole boat has to be aimed a couple of degrees to windward of the course it actually travels.

As the dinghy sailor lowers the centerboard, he or she might also allow the sail to aim its effort in a more forward direction by letting it out just a little. Now the airfoil and hydrofoil get down to work—against each other. As each begins to encounter faster flow (we are dealing in less than walking speed here, so "fast" is a relative term) each foil begins to produce lift. The centerboard produces lift to windward, as well as drag, while the sail produces lift to leeward, and slightly forward. It's the "slightly forward" that makes things happen.

Creating more lift (and causing less drag) is the Holy Grail of high-performance sail and keel design. (This also explains why there are now designers who specialize in "appendages," keels and rudders, and others who design hulls—both separate from the people who design the sails.) Of course, they have contrived a whole set of labels and rules to talk about it. Two important labels in this discussion are "center of effort" and "center of lateral resistance." These are really just two sides of the same coin because both centers involve foils—"effort" for the sails, and "lateral resistance" for the keel and rudder.

Now that computers are able to analyze the contribution of every carefully shaped square inch of foil surface, the center of effort and its twin, the center of lateral resistance, are much easier to find. Both centers are simply the sum of all of the lift and drag forces at work anywhere on the foil. If you had to attach a string somewhere on the sail and another on the underwater surface, and pull the boat along by these two strings—creating the same force and balance as a particular strength and direction of wind—the center of effort is the place where you would attach the sail's string, and the center of lateral resistance is the place you would have to attach



The center of effort (CE) is the position of the sum of all the lift and drag forces produced by the sails. The center of lateral resistance (CLR) is the equivalent position of all forces produced by the hull and its appendages. When the two centers are balanced against each other, the boat travels in a straight line *(top)*. When they are out of balance, the boat turns. Changing the rudder angle *(bottom)* shifts the position of the CLR aft so that the boat turns to leeward.