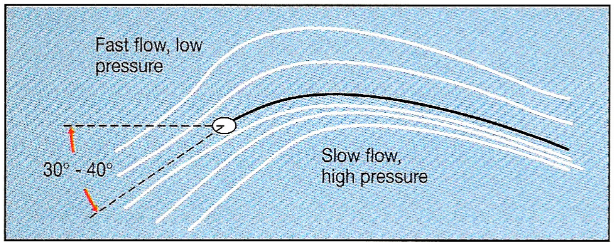

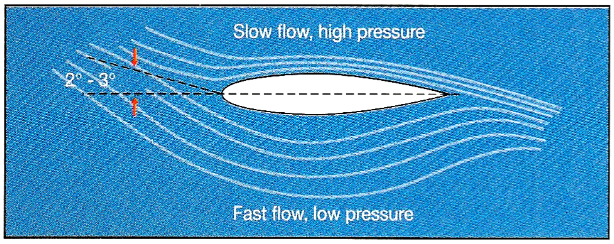

Thin foils, such as sails *(top),* must be presented to the wind at an angle in order to create a low-pressure area across their leeward surface. The sails try to move into the low pressure area, producing forward and lateral movement. Thick foils, such as fin keels *(bottom),* also must be presented to the water flow at an angle in order to create high- and low-pressure areas and "lift."

sailing carefully, the crew is trying to upset the equalization in favor of the driving forces—trying to make the boat accelerate. When the crew is successful, a larger drive is soon countered by a larger drag and, once again, the boat settles into a "steady state"—but at a higher speed.

Airfoils vs. hydrofoils

Sailboats and airplanes bear some kinship because both depend on a careful use of fluid motion over curved surfaces. But a sailboat operates between two fluid media—air and water, while a plane operates in only one. The airplane's airfoils (wings) both pull in one direction—upward.

The sailboat's foils pull in nearly opposed directions—the sails to leeward and the keel to windward. Each depends on the other to make the sailboat work—to make it move. Sails could not extract energy in any useful way without the work of the keel, and the keel could not do its work if the boat were not being pushed.

Historically, the airfoils on a sailboat (its sails) have received a lot more attention than the hydrofoils. Designers have developed complicated ways to make them more efficient over a range of wind speeds by changing their shape and their angle to the hull. On the other hand, hydrofoils have been left pretty much on their own while the boat is underway. But this is changing. Designers are now finding ways to modify the shape and orientation of fin keels too, as any America's Cup spectator knows.

Bernoulli's discovery

In the early 1700s, the Swiss scientist Daniel Bernoulli established that changing the velocity of air or water flow at a specific point brings about a consequent change in pressure at the same point. Bernoulli's theorem led to the principle of the venturi effect and the development of the curved foil. The most convincing demonstration of the venturi effect is easy to perform in the kitchen. First, run a stream of water from the faucet. Then, dangle a soup spoon by the tip of its handle and move its convex surface slowly toward the stream. Rather than being pushed away, as your intuition might suggest, it is pulled into the stream.

The most familiar practical application of the venturi effect is seen in the behavior of an airfoil such as an airplane wing. As the plane moves along a runway, the induced airflow (from the plane's motion) separates as it strikes the leading edge of the wing. The velocity of the airflow forced to travel over the airfoil's convex upper surface increases because it spans a greater distance than the air that travels beneath the wing.

Following Bernoulli's theorem, the increased velocity on the upper surface of the wing is accompanied by a decrease in pressure, relative to that on the under surface. Since a region of high pressure will try to push into one of low pressure, a force is produced. Aviators began calling this force "lift" and we use the same term when talking about boats. (The term "lift" also has another meaning, discussed later in this chapter.) Depending on the shape of the surface, the speed of the flow, the angle at which the foil meets the airflow and other factors, more or less lift is produced. The faster an aircraft's forward motion induces airflow across its wings, the greater the pressure differential and the greater the lift. Ultimately, the high pressure area beneath the wing, in attempting to displace the increasingly lower pressure area above it, lifts the wing—and the aircraft to which it is attached—upward and off the ground.

An asymmetrical airplane wing, curved on the upper surface and almost straight on the lower surface, can produce some of its lift even when it is pushed in a line parallel with the oncoming airflow—that is, with no "angle of attack." The sails on a sailboat, acting as a vertical wing or airfoil, ordinarily don't have thickness the way an airplane wing does. Without thickness and being symmetrical (because they have to produce lift alternately on both sides), sails must be presented to the flow of air at an angle. This is why sailboats lose their drive, or end up "in irons," when they are steered too close to the wind.

When sails are set at an efficient angle, air flows across their convex leeward surface and a low pressure area is created. The sail tries to move into it, impelled by the higher pressure on its windward side. This driving force created by the sails is transmitted to the hull through the mast, sheets and sail attachments. The boat begins to move, but not necessarily in the right direction—not yet.

At the same time that lift is being created, there is another force at work on the sails. This is the drag that results from friction and turbulence along the sail's surface and at its