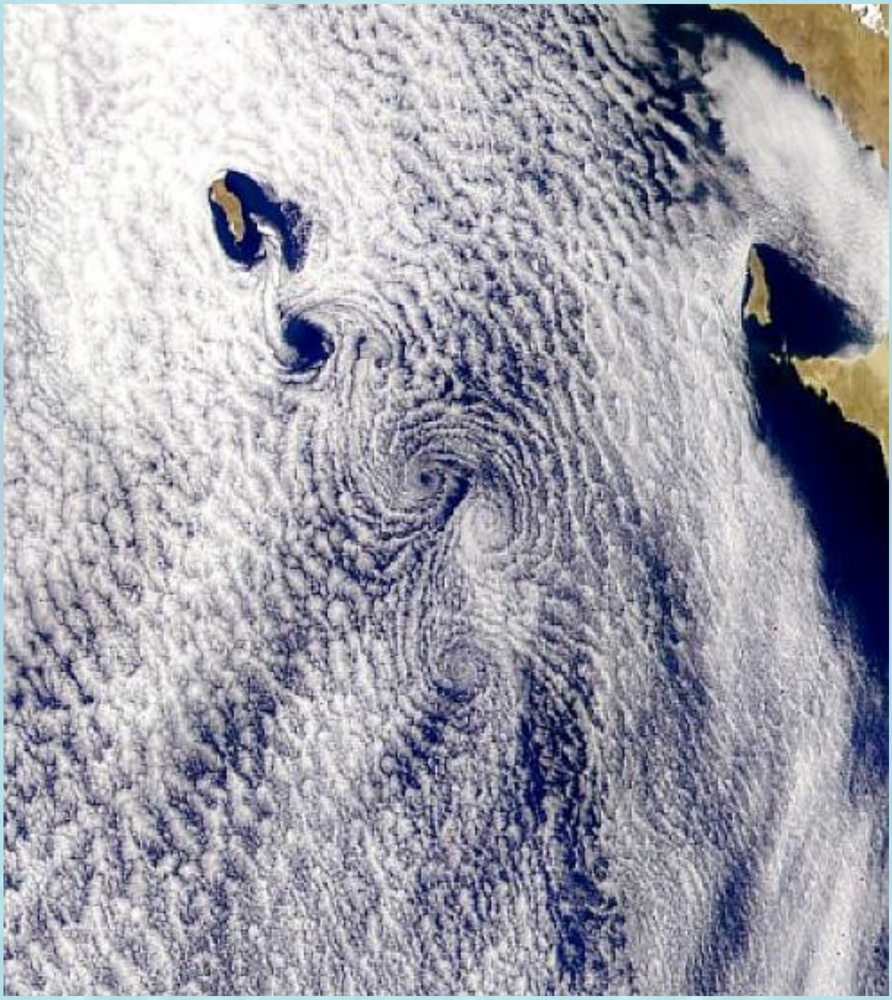
SCIENCE FOCUS: VON KARMAN VORTICES

Various Views of von Karman Vortices



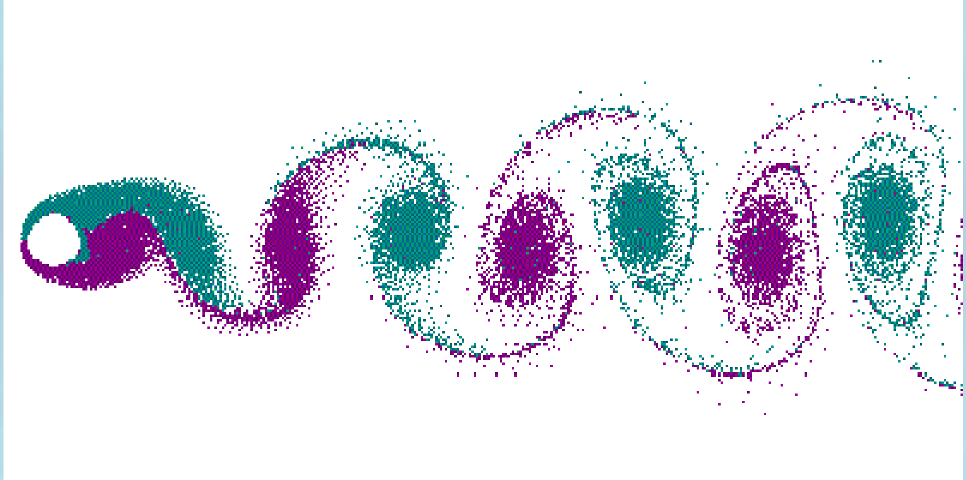
Both the ocean and atmosphere are fluids, in constant motion. On our limited "human"-scale, we are aware of this motion when we feel the wind blow, or when we encounter a current running along the beach while swimming. Yet our eyes alone can rarely observe the larger scale of fluid motion in the ocean and atmosphere.

SeaWiFS had the unique ability to observe evidence of fluid motion in both the ocean and the atmosphere from space. Many other meteorological satellites can observe cloud patterns that show the fluid dynamics of the atmosphere, but SeaWiFS (under the right conditions) could also view plankton blooms that displayed fluid motionin the marine environment.

The phenomenon that is shown in the image of Guadalupe Island at the top of this page (acquired on August 20, 1999) features a ubiquitous occurrence in the motion of fluids—a *vortex street*, which is a linear chain of spiral eddies called **von Karman vortices**. Von Karman vortices are named after Theodore von Karman, who first described the phenomenon in the atmosphere. Dr. von Karman was a co-founder of NASA's Jet Propulsion Laboratory.

von Karman vortices form nearly everywhere that fluid flow is disturbed by an object. In the cloud images shown on this page, the "object" that is disturbing the fluid flow is an island or group of islands. As a prevailing wind encounters the island, the disturbance in the flow propagates downstream of the island in the form of a double row of vortices which alternate their direction of rotation.

The image below (courtesy of Cesareo de la Rosa Siqueira at the University of Sao Paulo, Brazil) is from an animation showing how a von Karman vortex street develops behind a cylinder moving through a fluid. The animation can be seen here: **Kármán vortex street**



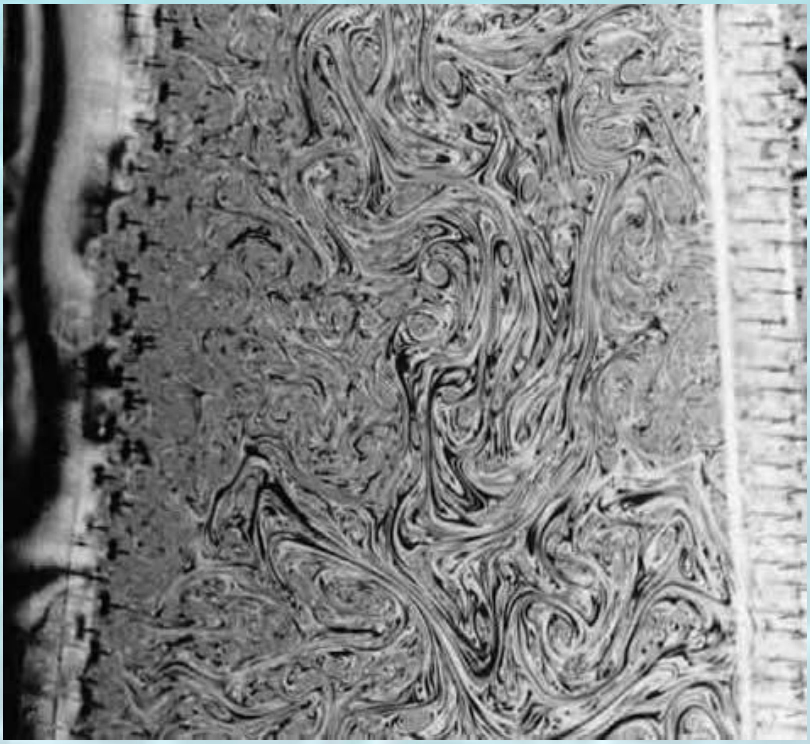
Technically speaking

"As a fluid particle flows toward the leading edge of a cylinder, the pressure on the particle rises from the free stream pressure to the stagnation pressure. The high fluid pressure near the leading edge impels flow about the cylinder as boundary layers develop about both sides. The high pressure is not sufficient to force the flow about the back of the cylinder at high Reynolds numbers. Near the widest section of the cylinder, the boundary layers separate from each side of the cylinder surface and form two shear layers that trail aft in the flow and bound the wake. Since the innermost portion of the shear layers, which is in contact with the cylinder, moves much more slowly than the outermost portion of the shear layers, which is in contact with the free flow, the shear layers roll into the near wake, where they fold on each other and coalesce into discrete swirling vortices. A regular pattern of vortices, called a vortex street, trails aft in the wake."

The "Reynolds number" is the ratio of inertial forces to viscous forces in a fluid. The Reynolds number indicates the likelihood of turbulent (rather than laminar) flow in a fluid. As an example, two paddles moving at the same speeds—one through a bucket of water and one through a bucket of paint—will have different Reynolds numbers associated with the fluid flowing around them. The Reynolds number in the tub of paint will usually be lower.

Von Karman vortices form at all scales of fluid motion. The picture below shows a complex vortex street formed in a flowing film of soap with two cylinders in the fluid flow.

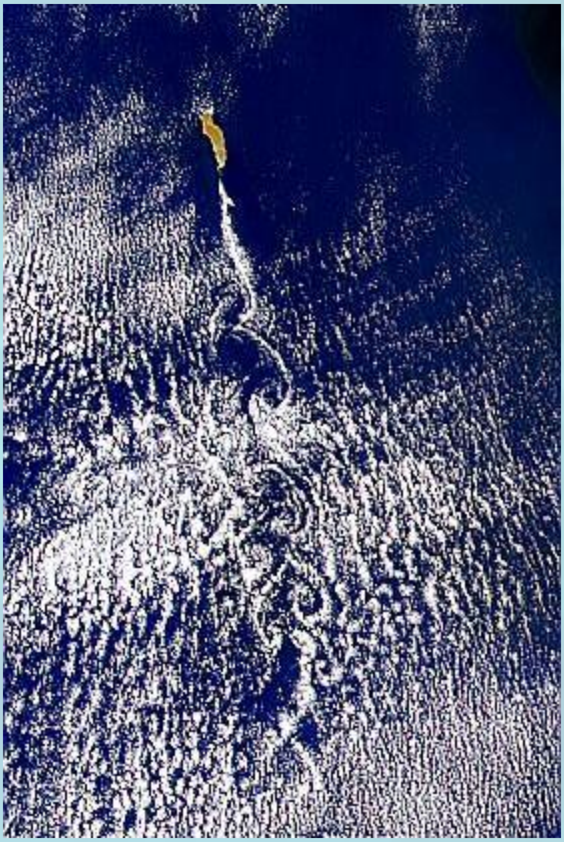
The picture at right shows what happens when the fluid flow rate is increased, and a comb (rather than a single cylinder) is placed in the film. (These soap film vortex images are courtesy of Dr. Maarten Rutgers, in the "Science" section, "Vortex Street" subsection of his Web site. To see how the apparatus works, click "Soap Intro". The picture below is cropped from a larger version in the "Vertical Combs" subsection)



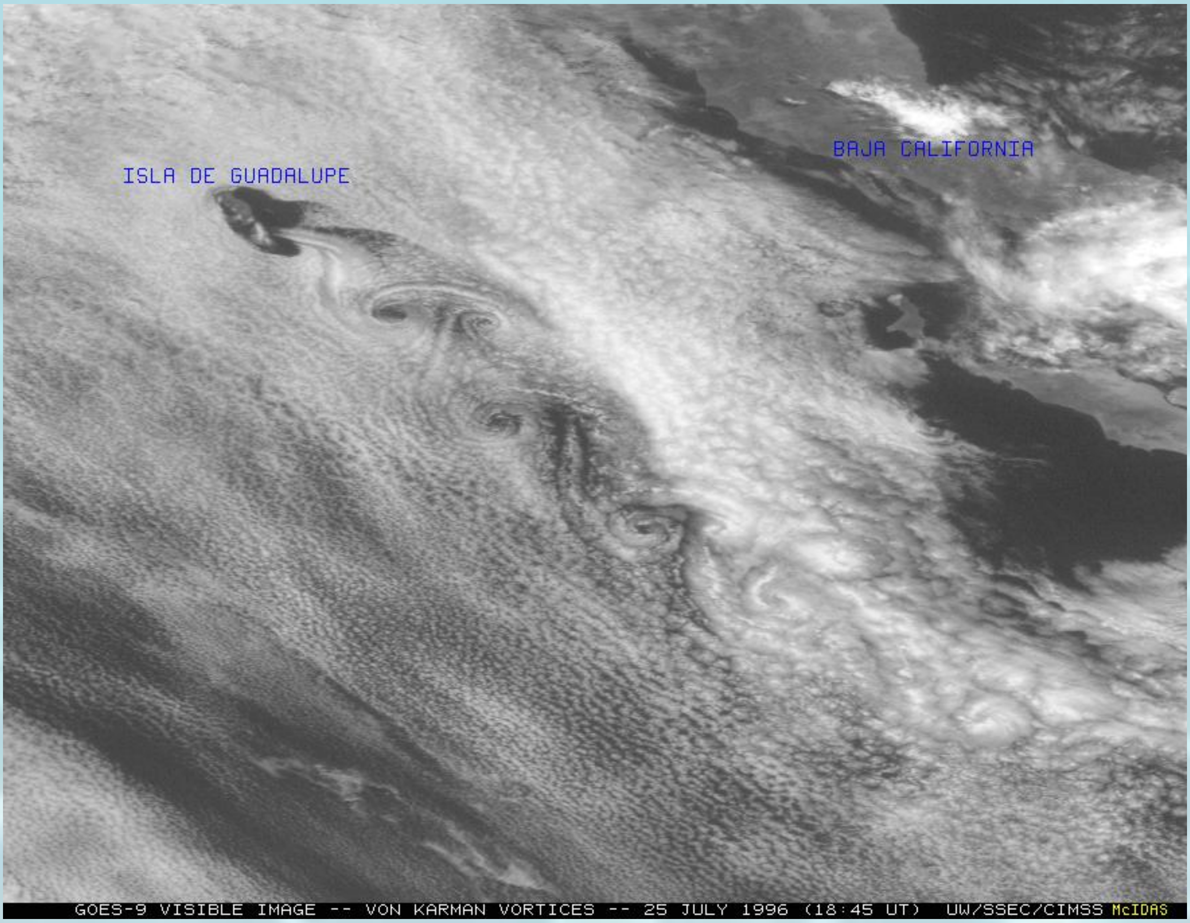
Compare the soap film comb image on the previous page to these SeaWiFS images of phytoplankton blooms near the Shetland Islands in the North Sea (top) and the Falkland Islands east of Argentina (bottom).

It is clear to see that vortex patterns form on both the large and small scale. These patterns are particularly impressive in the atmosphere, the cloud spirals that form in the wind-wake of islands. On the next pages are several more SeaWiFS images of von Karman vortex streets in clouds; a unique SeaWiFS image of swirls in sea ice (see note) on the coast of Hudson Bay; and links to other images of vortex streets taken from Skylab, the Space Shuttle, and a geostationary meteorological satellite (GOES).

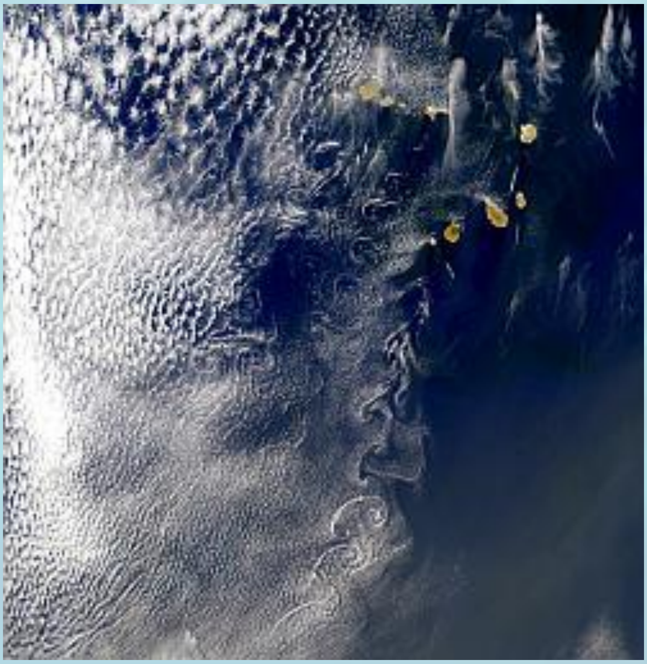
Guadalupe Island vortex street from SeaWiFS, March 10, 2000 (right)

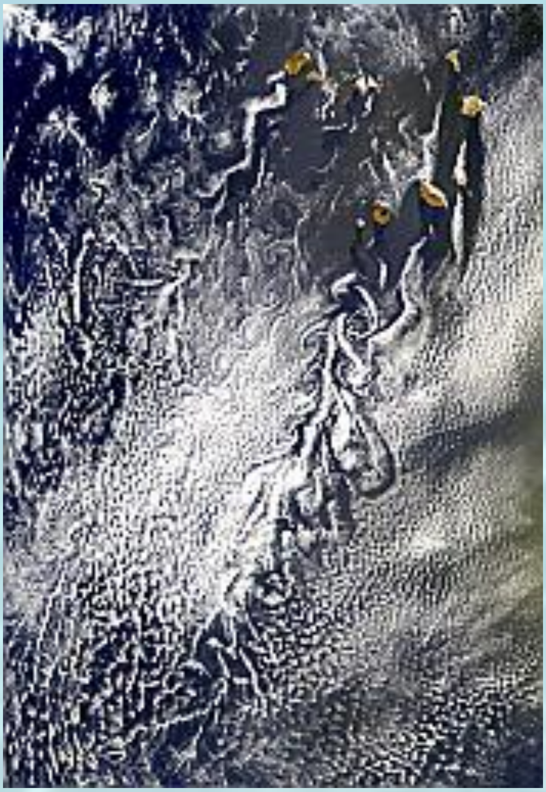


Guadalupe Island vortex street from GOES-9, July 25, 1996 (below)



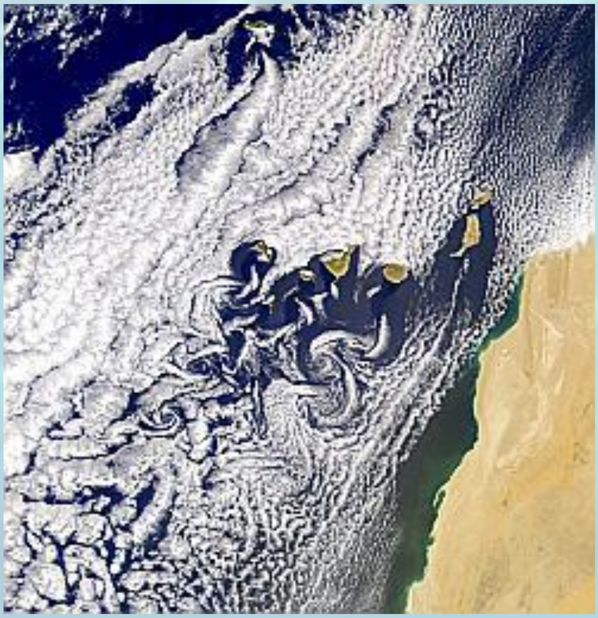
Vortex Streets, Cape Verde Islands





Images acquired January 1, 2000 (top left); January 19, 2000 (top right), and May 8, 2000 (left).

Vortex streets, Canary Islands:



Images acquired April 24, 2000 (left) and June 4, 2000 (right).

Swirls in Hudson Bay, Canada:

Note: It's not absolutely certain that this is ice. Instead, it could be fog. The sharpness of "cracks" in the center and right of the image make ice a more likely candidate. The image was acquired July 22, 2000.

Astronaut images

von Karman Vortices over the Pacific Ocean, from Skylab, August 1, 1973.

von Karman Vortices over Heard Island, Antarctica, from the Space Shuttle, November 14, 1994

von Karman Vortices over Socorro Island, Mexico, from the Space Shuttle, May 16, 1992

A final note: Studies of insect flight have revealed that one facet of their flight dynamics is their ability to borrow energy from the vortices that form around their wings during flight. Normally the vortices are simply lost energy, also called "drag". Yet insects can recapture some of the energy in the vortices and use it to aid their flight speed and maneuverability.

The text from the link is provided below. The research was performed at the University of California – Berkeley.

Berkeley (6/15/99) -- Insects have been flitting about the planet far longer than any other creature, yet how they manage to stay aloft has been a mystery. Now, a University of California, Berkeley, biologist has solved the riddle.

Using a pair of robotic wings they've dubbed "robofly," Michael Dickinson and his colleagues at UC Berkeley have found three distinct wing motions that not only allow insects like flies and bees to stay airborne, but also let them steer and execute amazing acrobatic maneuvers. These mechanisms seem to be common to most insects, and perhaps even to the hummingbird. (For video of robofly and diagrams, click here.)

"Engineers say they can prove that a bumblebee can't fly," said Dickinson, an assistant professor of integrative biology. "And if you apply the theory of fixed wing aircraft to insects, you do calculate they can't fly. You have to use something different.

"We now have a unified theory of insect flight aerodynamics that explains how they can steer and maneuver. We've solved the old riddle."
The team's discovery could help speed the development of small flying robots, which must be designed around different physical principles than larger flying craft. Dickinson is part of a group of engineers and scientists at UC Berkeley now designing such robotic insects.

Dickinson, postdoctoral researcher Fritz-Olaf Lehmann, now at the University of Würzburg am Hubland in Germany, and graduate student Sanjay Sane report their conclusions in this week's issue of the journal Science.

"Insects are the most successful group of macroscopic organisms on Earth, and they were the first to take to the air. Their life seems centered around flight," Dickinson said. "Understanding the evolution and the aerodynamics of flight is a great problem in biology. With insects, we didn't really know how the damn things could stay in the air.“

The problem is that the dynamic nature of flapping wings, especially small wings, can't be approximated by a fixed wing and steady airflow around it, as with airplanes. In that situation, air travels faster over the top of the wing than along the bottom, generating lift.

"Steady state aerodynamics of airplanes works well for birds, for the most part, but insects have always been a problem," Dickinson said. "If you treat a bird wing like an airplane wing and at any given time calculate the speed and lift, then sum it up over the entire stroke, it works fairly well to explain how the bird can stay aloft. With insect flight it fails miserably.“

To find out what other forces insects take advantage of, he and his coworkers constructed a pair of 25-centimeter-long (10 inches) Plexiglas wings, modeled after the wings of the fruit fly Drosophila melanogaster, and immersed them in a tank of mineral oil. The thick, viscous oil is needed so that the scaled-up wings, flapping slowly, will react the same way as smaller, one-millimeter-long fruit fly wings beating rapidly in the air.

Six motors -- three on each wing -- move the wings back and forth and up and down, and rotate them, reproducing the exact motions of a fruit fly's wings. Sensors at the base measure the forces on the wings.

"This device gives us the instantaneous force on the wing, that is, how much the forewings are working throughout the stroke," he said. "This is the most straightforward way of testing -- we can make it fly any way we want and measure the resulting forces.“

What they found is that insects use three distinct but interacting techniques to gain lift, that is, to counter gravity and stay in the air. Interestingly, the flexibility of the wing seems unimportant, Dickinson said, and fruit fly wings are very rigid when flapping.

One of the mechanisms is called "delayed stall," which Dickinson and others had identified earlier as an important lift mechanism. This occurs as the insect sweeps its wings forward at a high angle of attack, that is, cutting through the air at a steeper angle than that of a typical airplane wing. A fixed wing, like that of an airplane or bird, would stall at such a high angle, losing lift, suffering increased drag and ending in disaster.

Under some conditions, however, a structure called a "leading edge vortex" can form and sit on the top surface of the wing to create lift. The Concorde supersonic airplane takes advantage of this vortex during takeoff, as explained by Charles Ellington at Cambridge University.

About five years ago, when insects were found to use delayed stall, some thought this was the answer to the question of how insects fly, Dickinson said. Subsequent measurements showed that delayed stall wasn't the complete answer, however.

Dickinson now has discovered two other techniques used by insects. One is called "rotational circulation" -- basically, as the insect wing nears the end of its stroke, it rotates backward, creating backspin. Just as backspin lifts a tennis ball, so it can provide extra lift for an insect.

Finally, a mechanism called "wake capture" gains an insect added lift by recapturing the energy lost in the wake. As the wing moves through the air, it leaves whirlpools or vortices of air behind it. If the insect rotates its wing before starting the return stroke, the wing can intersect its own wake and capture extra oomph to keep the insect aloft.

"It's really nifty. It's a way of capturing energy that is lost," he said. "Insects can get lift from the wake even after the wing stops.“

Dickinson said that different insects use these mechanisms to varying degrees. For example, the most acrobatic insect around, the hover fly, appears to use delayed stall very little, but makes great use of rotation circulation and wake capture.

At the opposite extreme, butterflies use the three mechanisms very little, but rely primarily on simple steady state aerodynamic principles when they glide or flap their wings.

He suspects, too, he said, that hummingbirds -- "essentially glorified insects" -- use many of the same mechanisms as small insects.

The fact that many insects have two sets of wings doesn't change anything either, because the second set -- the hindwing -- generally follows the motion of the forewing and does not flap independently.

Insects have had to adapt new modes of flight because of their small size: the average insect is only four to five millimeters long, or about one fifth of an inch.

"In order to fly in this size range, insects have had evolve these mechanisms. You can't fly like a bird if you're the size of an insect," Dickinson said. "It would be spiffy if we could exploit these mechanisms, too, by building an insect robot. But you can't build them now based on known principles -- you have to fundamentally rethink the problem."

Many more questions remain, such as how insects use these mechanisms to steer or, like flies, land upside down. For example, Dickinson suspects that insects maneuver by changing the point in the stroke at which they begin to rotate their wings.

"These rotational mechanisms -- wake capture and rotational circulation -- are very responsive. A tiny change in timing of wing rotation can create a big change in the force produced," he said. "Insects use this to steer, starting rotation earlier in the wing on the outside of the curve."

Eventually, understanding the mechanics of flight will help Dickinson in his real interest, the neurological control of insect flight -- how an insect's brain, nerves, muscles and skeleton interact to produce some of the most versatile fliers on the planet.

The work was supported by grants from the National Science Foundation, the Defense Advanced Research Projects Agency and the Office of Naval Research.