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Microscopic scales enhance a butterfly's flying efficiency

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Ever catch a butterfly and noticed what looks like dust coating your fingers? They're the scales covering the insect's wings, and they allow it to slip through the air.

Monarch butterflies follow a migration pattern unlike any other known species of their kind—they can travel more than 4000 km from the northern US or Canada down to central Mexico to hibernate. At first glance, such a long trek is unexpected: With short, broad, and large wings relative to their body, butterflies look like no other flying animal. But that achievement may be the result of more than just soaring high to catch the right wind currents.

Classified scientifically with moths as Lepidoptera (Greek for "scaled wing"), butterflies can have more than a million microscopic scales covering both sides of their wings. The scales vary in shape, but they typically measure about 0.1 mm and are arranged like shingles on a roof, as shown for a monarch in figure 1. In addition to repelling water, the scales give the insects their unique color pattern, which helps them avoid predation, regulate temperature, and attract mates. And their microgeometry reduces skin-friction drag by as much as 45%. This Quick Study explains how.

Butterfly scales

Flying efficiency drives the diversity of wing shapes in insects, and size is an important factor. Higher flapping frequencies are used by smaller winged insects, such as flies (200 Hz), and lower frequencies by larger insects, such as monarchs (10 Hz). Most butterflies, including monarchs, fly within a few meters of the ground, though monarchs have been observed during migration to reach altitudes of more than 1 km, where they can glide for miles in the wind currents. When cruising near the ground and flapping their wings, they can reach speeds of up to 5 m/s—about half the speed of Usain Bolt, the fastest human on record.

In 2017 Nathan Slegers and I worked with colleagues to analyze the flapping motion and trajectory of monarch butterflies, first with their scales intact and then with the scales removed. For one thing, the experiment disproved the myth that scales are essential for the insect to fly. More importantly, gently removing the scales, which are anchored to the wing much as bird feathers, decreased a butterfly's weight by an average of just 9.5%.

Yet in a study of more than 200 flights by 11 specimens, the removal decreased a monarch's mean climbing efficiency—defined as the total change in kinetic and potential energy achieved by the butterfly per flap—on average by 32%. The scales impart a unique, advantageous geometry: They are angled upward and form microscopic cavities that improve the wing's aerodynamics.

Aerodynamics of flight

As shown in figure 1, the four fundamental forces on a butterfly in flapping flight are the lift (**L**), which counters the weight (**W**),

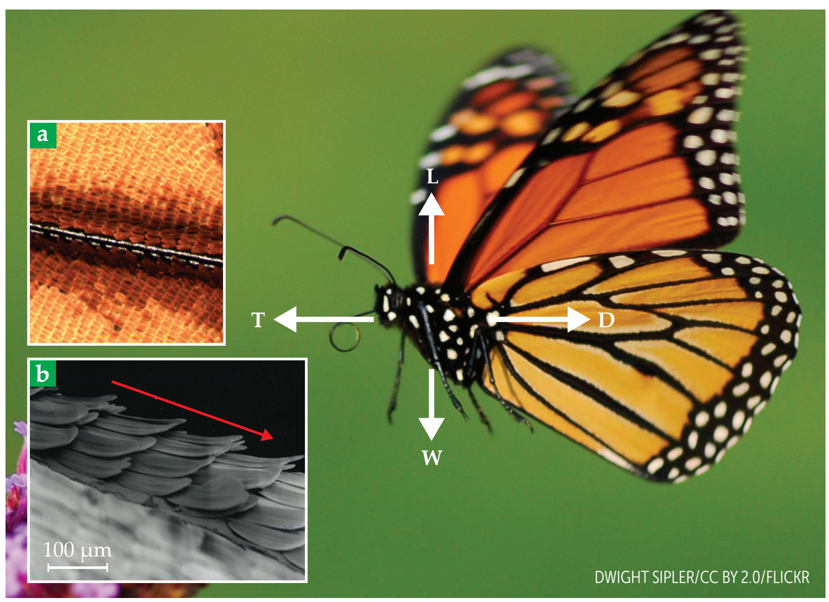

FIGURE 1. A MONARCH BUTTERFLY experiences the forces of lift (**L**), which counters its weight (**W**), and of thrust (**T**), which counters its drag (**D**). **(a)** A microscope image of a wing reveals discrete scales, each about 0.1 mm long, that form rows perpendicular to wing veins (black). **(b)** Microcavities are created on the wing's surface as the scales' tips curve upward. The orientation of airflow (red arrow) transverse to the cavities decreases the skin friction. (Insets adapted from N. Slegers et al., *Bioinsp. Biomim.* **12**, 016013, 2017.)

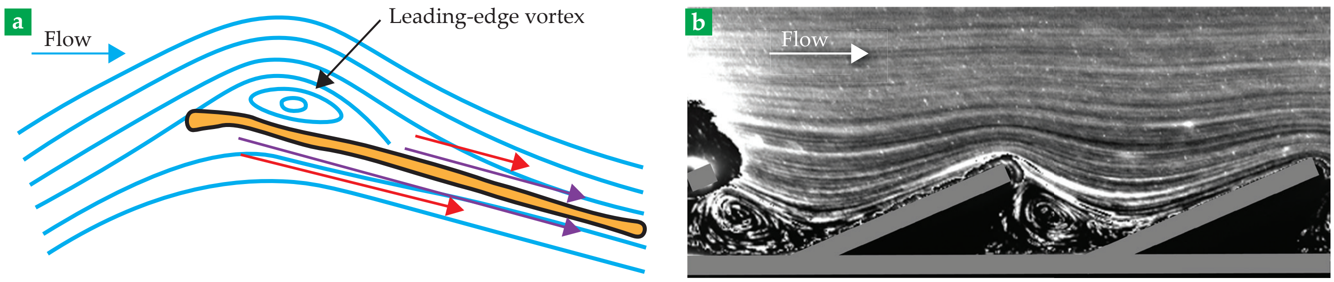

FIGURE 2. STREAMLINE PATTERNS. (a) As air flows over a butterfly's wing during flight, a leading-edge vortex forms on the upper surface. As the viscous air travels across the wing, it generates skin friction, which creates drag (red arrows) on both sides of the wing. Without the so-called roller-bearing effect created by the wing's scales, the drag would be greater (purple arrows). **(b)** In a fluid visualization experiment employing mineral oil, the tiny cavities between scales (gray bars) trap fluid, which then rotates in small vortices. As if sliding across roller bearings, the outer air flows over the surface with less skin friction. (Adapted from S. Gautam, PhD thesis, U. Alabama, 2021.)

and the thrust (**T**), which counters the drag (**D**). Three of them—lift, thrust, and drag—are generated on the wings. To climb, the insect's lift and thrust must be greater than its weight and drag. Furthermore, the only ways by which net lift, thrust, and drag are imparted to the wings are through the pressure (normal force per unit area) and shear stress (tangential viscous force per unit area) of air in contact with the wings.

As the insect flies, air passing over each wing—either during its downward stroke or while gliding motionless—produces a leading-edge vortex, shown in figure 2a. The swirling flow generates low pressure inside the vortex, and the resulting pressure difference across the wing generates both lift and thrust. The drag primarily arises from the shear stress.

In 2020 Christoffer Johansson and Per Henningsson used slow-motion cameras and flow measurements to discern a butterfly's distinct flight patterns. They found that the thrust is largely produced at the end of the upstroke, when the flexible wings clap together and press out the air trapped between them. The airflow can become complex, unsteady, and three-dimensional. The shear stress, or skin friction, of viscous air passing over the wing makes up about half the total drag force during gliding flight. The other major contributor comes from the swirling energy, known as induced drag, left behind in wake vortices.

A conservative estimate of the monarchs' glide ratio—the ratio of lift to drag force—is 4:1. A modest estimate for the skin friction during gliding flight could be around 10% of the lift. With their wings' low aspect ratio, butterflies are inefficient flyers, at least compared with a Boeing 747, whose glide ratio is around 17:1. A mechanism to reduce the skin friction would allow monarchs to move their lightweight bodies and large wings through the air with significantly less resistance.

Controlling skin friction

The skin friction on a butterfly's wing comes from the formation of a laminar boundary layer, a region of smooth viscous flow with a velocity difference between that of the wing and the surrounding air. Along the wing, the velocity of the air must match that of its surface—the so-called no-slip condition in fluid mechanics. But the presence of microcavities formed by the scales alters how the air interacts with the wing surface.

Because the scales are so small and the airflow over them is viscous, the Reynolds number—the ratio of inertial forces to viscous forces—is less than 10 in the cavities under the scales. At such a low Reynolds number, the flow is steady and smooth. Were the Reynolds number to increase, instabilities in the flow would emerge. My group replicated that low Reynolds number flow in the lab by replacing air with high-viscosity mineral oil and scales with manufactured plates, which increased the size of the scales 300-fold. We tested bioinspired models of the scale surface using cavity wall angles between 22°and 45°.

When the fluid passes over the scales' cavities transverse to the rows of scales, small vortices become trapped, as shown in figure 2b. Those minuscule wheels of air essentially become part of the wing surface and are independent of the outer flow. The outer flow can then skip over the surface—the so-called roller-bearing effect—thereby negating to some extent the no-slip condition. For the low Reynolds number flow experienced by a butterfly's scales during flight, lab results revealed a reduction in skin-friction drag of at least 26% and as high as 45%, compared with that over a smooth surface. (See figure 2a.)

Our latest results show that when the cavity Reynolds number is increased well above 10 (to 80 or more), that beneficial effect disappears—the skin friction drag increases—because flow in the small vortices becomes unsteady and mixes with the outer flow above it. A butterfly's tiny scales thus function precisely for the flight speeds that the insect usually experiences. Were the scales much larger, they would generate a higher cavity Reynolds number, and the flow-control mechanism that boosts flight efficiency would be lost.

Additional resources

- N. Slegers et al., "Beneficial aerodynamic effect of wing scales on the climbing flight of butterflies," *Bioinsp. Biomim.* **12**, 016013 (2017).
- L. Johansson, P. Henningsson, "Butterflies fly using efficient propulsive clap mechanism owing to flexible wings," *J. R. Soc. Interface* **18**, 20200854 (2021).
- D. Gibo, "Altitudes attained by migrating monarch butterflies, *Danaus p. plexippus* (Lepidoptera: Danaidae), as reported by glider pilots," *Can. J. Zool.* **59**, 571 (1981).
- A. Lang et al., "Sharks, dolphins and butterflies: Micro-sized surfaces have macro effects," *Proceedings of the ASME Fluids Engineering Division Summer Meeting*, paper no. FEDSM2017-69221 (2017).
- S. Gautam, "An experimental study of drag reduction due to the roller bearing effect over grooved surfaces inspired by butterfly scales," PhD thesis, U. Alabama (2021).