Insect Inscriptions

Hunting for human symbols in gently fluttering wings

By IVAN AMATO

ith its misty cascades, Iguassu Falls punctuates the already steamy border between Paraguay, Argentina and Brazil.

"There, for the first time, I saw butterflies with the number 89 on their wings," recalls nature photographer Kjell B. Sandved. "Some of them even have more than one number."

They're easy to photograph, too, he says. "That's because when you go there, you always sweat. They smell you and love it, and they alight right on your hand."

Before Sandved began his search for fluttering numerals, he had already found a variety of letters on the wings of Lepidoptera – the diverse taxonomic order that includes the world's 200,000 or so species of butterflies and moths. The alphabet project sprang from a chance discovery made nearly 30 years ago, when Sandved was working as a volunteer at the Smithsonian Institution's National Museum of Natural History in Washington, D.C.

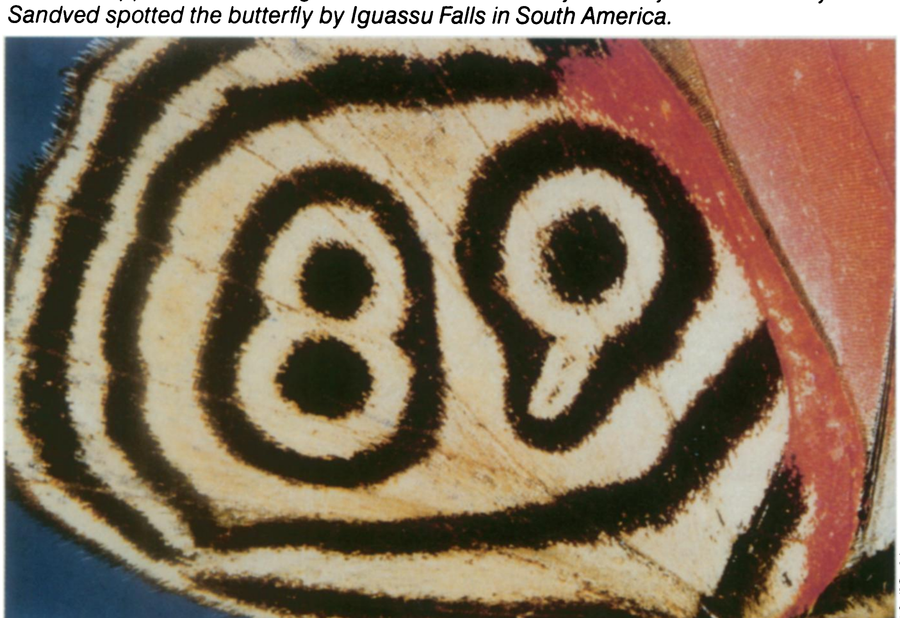
"I went up into a dusty attic of the museum," Sandved recounts. There he found boxes and boxes of uncatalogued Lepidoptera. "I opened one of these boxes and saw a beautiful letter F."

That was in 1961. From there, he says, "I started looking around for more letters" – and not just in boxes. Over the next 15 years, Sandved tracked down and photographed thousands of butterflies and moths in a quest that took him from the Peruvian Andes to the rain forests of New Guinea to the highlands of Malaysia. In the mid-1970s, he published his first series of photos featuring colorful pointillist letters emerging in the breathtaking arrangements of dust-speck lepidopteran scales.

Today, Sandved's office in Washington, D.C., is crammed from floor to ceiling with his photos, posters and slides. He has managed to assemble the entire alphabet several times over. He has also photographed wing versions of the digits zero through nine, ampersands and question marks, human-like faces and blinking eyes, Greek letters like Ω and π, the Scandanivian ø and the Germanic ümlaut vowels. He has even amassed a series of animal images from the wings of butterflies and moths, which he keeps in a black portfolio labeled "Noah's Ark."

"I have wings looking like algae, looking like shells and fishes and cacti," he says – not to mention some remarkably detailed images of entire spiders and beetles, all discernible in the patterns of lepidopteran scales.

This "89" appeared on a wing of a "hairstreak" butterfly of the Lycaenidae family. Sandved spotted the butterfly by Iguassu Falls in South America.



Photos: Sandved

hough people tend to perceive Sandved's typographical discoveries in an anthropomorphic context, the wing patterns evolved to convey distinctly nonhuman messages. Sandved and other lepidopterologists suspect, for instance, that the circles or O's seen on so many moths and butterflies evolved to appear as eyes. Many animals, including fish and birds, sport similar circular motifs. A striking example is the male peacock, which spreads its tail plume to reveal a profusion of vivid eyespots. A potential assailant might think twice before messing with those glaring eyes.

Large, dramatic eyespots on butterflies and moths may likewise discourage hungry birds and other predators. The spots can appear eerily lifelike; Sandved says he has found moths with eye designs that actually seem to blink when a hind wing eclipses a front wing.

On the other hand, small spots on wing edges might serve to divert a predator's attention from more critical tissues such as the insect's head and body, Sandved suggests. In such cases, he speculates, the lepidopteran logic goes as follows: "If my primary wing designs haven't concealed me from you or frightened you away, and you're determined to bite me, then at least bite here, on the edge of my wing, where I will be injured the least." He has photographed a butterfly with spider-mimicking designs on the edges of its wings, where the unusual patterns might offer a similar last-ditch line of defense.

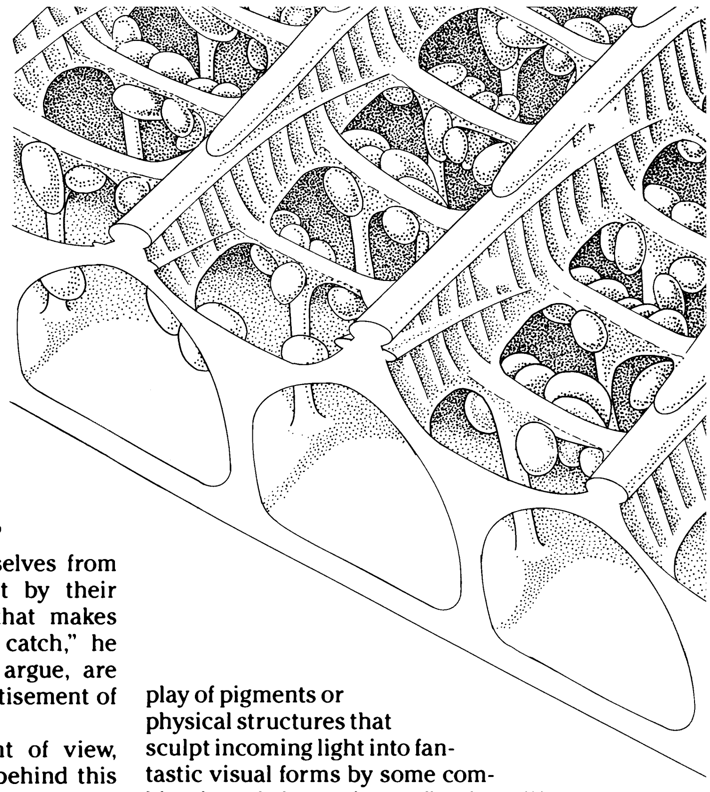
Some wing designs spill over to other parts of the anatomy. In Venezuela, Sandved found a moth with an L on two of its wings. During the day, when this moth needs to conceal itself, the Ls connect with lines on its other two wings and outstretched legs to give the insect the appearance of a shriveled leaf complete with "veins," he says. At night, the leaf comes alive, flitting about in search of food and mates.

olor has its own significance in the lepidopteran realm, and is one obvious attribute separating the moths from the butterflies. Moths, whose species vastly outnumber those of butterflies, rely mainly on the cloak of night for defense against predators. The pressure to conceal has driven their evolution, Sandved says. Rather than advertise their presence with bright colors, moths tend to blend into their surroundings with subtle earth tones. And because moths communicate with each other primarily by smell, their plain wrappers pose no handicap in courtship.

Butterflies, in contrast, communicate visually and are active during the day. "Butterflies are very visual creatures," says Thomas Eisner, a chemical ecologist and longtime butterfly researcher at Cornell University. "Their ability to spot one another from a distance is crucial."

The broad palette of visible colors tells only part of the story, he adds. About 20 years ago, Eisner and his colleagues showed that the intricate layered structures of scales in butterfly wings can produce intense ultraviolet reflections. These reflections, while invisible to people, provide important cues to other butterflies during courtship, he says.

Eisner has begun floating a new evolutionary rationale for butterfly colors.



Portion of typical butterfly or moth scale. During scale development, vertical and horizontal structures form an airy architecture. In many scales, incoming light gets transformed into brilliant, iridescent colors as it interacts with systems of ribs, stacked ridges and other structural patterns. Colors also arise from pigment granules, shown here attached to the scale's girders.

Ghiradella et al.

Butterflies distinguish themselves from other flying insects in part by their erratic flying styles, "and that makes them extremely difficult to catch," he notes. "Butterflies, I would argue, are colorful as a collective advertisement of their being hard to catch."

From the butterfly's point of view, Eisner fleshes out the logic behind this defense tactic: "I know you spotted me from 50 yards, but if you take off after me, you'll have a hard time catching me. And even if you grab me, I'm slippery because my scales slide off easily. You'll find that I'm all candy wrapper and no candy."

The thin, scaly wings don't make delicious or nutritious eating, Eisner says. Bright colors may help predators learn quickly that this erratic, slippery snack just isn't worth the effort.

very exquisite pattern on a quivering wing reflects the special properties of the scales that combine, like pixels on a television screen, to create the overall design. Zooming down to the microscopic level of individual scales—each roughly 50 by 100 microns—reveals a breathtaking view of functional bio-architecture.

On a square centimeter of a typical wing, tens of thousands of scales attach with tiny stems and overlap like cedar shakes to form unbroken coverage. During the insect's pupa stage, individual wing cells metamorphose into "ornate hollow shells containing struts, pillars, pigment granules and/or more elaborate constructions," says Helen Ghiradella, a specialist in butterfly scale morphology at the State University of New York at Albany. A day or two before the adult emerges from the pupa, the watery interior of each scale cell disappears, leaving behind a tough, nonliving, light-manipulating microarchitecture. "The astonishing thing is that a single cell is doing all of this," Ghiradella says.

Each scale's color arises from an interplay of pigments or physical structures that sculpt incoming light into fantastic visual forms by some combination of absorption, reflection, diffraction, scattering and interference effects.

Browns and blacks come most often from melanin pigments, which are diffusely distributed throughout the scale, says research entomologist Donald Davis of the National Museum of Natural History. Both the melanins and the pteridine compounds that generate the reds and yellows are by-products of metabolic activity that took place when the cells were still alive in the late pupa stage. Pteridines often reside in "little bags [pigment granules] hanging down inside the scale that you can see through little transparent windows," Davis says. The "windows" are the spaces between the struts and other structural elements that make up the scale's solid framework.

ome of the most breathtaking butterfly colors — the brilliant and iridescent blues and greens — emerge from the way light diffracts, refracts and scatters from the layers, lattices and ribbed walls of the scales, Ghiradella points out. For example, thin chitin (structural polysaccharide) layers stacked within the bodies of some scales cause incoming light waves to interfere with each other and produce iridescent colors like those seen in soap bubbles or oil films. Latticeworks that look like densely packed bubbles surrounded by a chitinous solid use both interference and scattering to produce an opal-like iridescence.

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particular configuration. Otherwise, it could get caught in a loop: looking at a set of boxes, rejecting that configuration, storing no information, then not knowing whether it had checked that configuration, looking at it again and so on.

To avoid getting caught in such a loop, the demon ends up with a memory filled with a string of essentially random digits distinguishing between the useful arrangements and the rejected arrangements. There's no compact way of expressing this information, Zurek says. The extra cost of erasing these digits exactly cancels any energy gain elsewhere in the system.

"In other words, rare fluctuations don't do you any good," Zurek says. Caves, Unruh and Zurek have prepared a brief paper for publication in PHYSICAL REVIEW LETTERS that clarifies the situation.

Are there any other potential loopholes? Zurek, for one, thinks that there's at least one more worth exploring.

"A lot of our original thinking had to do with a situation where the Maxwell's demon is completely deterministic," Zurek says. "In other words, it works like a computer should. One instruction is completed before it goes on to the next instruction."

What isn't so clear is what would happen if the demon could "wander" a little. What if the demon knew its instructions but wasn't quite sure of the order in which to carry them out? The demon would then proceed from one step to another, going forward or backward, in a somewhat random fashion. In the long run, that might allow the demon to extract some work from the system.

"It sounds fanciful, but I think there's a loophole there to be closed," Zurek says. "I have no doubt what the outcome of the argument is going to be, but I'm still missing a nice way of stating the reason for the demon's failure – from the demon's point of view."

As this latest episode demonstrates, tangling with Maxwell's demon and the second law of thermodynamics is not for the faint of heart. Theorists entering the fray must be unusually adept at their craft – and extremely careful. "It's such a confusing thing, and so many people get snagged," Bennett says.

The episode also shows the potential for applying a branch of theoretical computer science, known as algorithmic information content analysis, to questions in thermodynamics. For example, such an information-based approach provides an alternative way of looking at the degree of disorder, or entropy, in a system.

Scientists usually express a system's degree of disorder in terms of statistical measures of, say, the distribution of molecules in the system. But it's also possible to consider the changes in entropy associated with acquiring or erasing the information someone needs and uses to make a measurement or to describe the state of a physical system.

"Only algorithmic information content allows one to consistently develop a formalism from the point of view of the entity that requires information," Zurek says. "I suspect this will have implications not only for second-law thermodynamics but also for things like quantum-theory measurements."

"People made mistakes in the past by thinking that information was almost magically separate from physics – something separate from the medium in which it was stored," Bennett says. In reality, "the value that a bit [of information] could have is just like the volume of space a molecule could be in."

In other words, the distinction between information and physical objects is somewhat artificial. "Thinking of information as outside of physics – as being merely in the human mind – is silly," says Bennett. "Information *is* in physics." □

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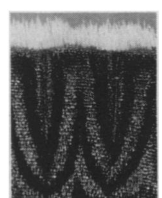
Ghiradella says she has found both types of structures in different scales of the same butterfly. The distances between individual layers and "bubbles" usually fall in the 300-to-700-nanometer range – the same range of electromagnetic wavelengths that humans see as colors. For some effects, such as reflecting shorter-wavelength ultraviolet light, the distances are even smaller.

Davis has examined multilayered scales in which chitinous layers alternate with "air blankets" at specific distances that determine which wavelengths, or colors, of incoming light will get reflected. These thin, chitin-air layers act "like stacked oil slicks," Ghiradella adds. In some cases, they function as prisms, refracting different colors at different angles so that the wings assume different hues depending on the observer's viewing point.

Besides serving as pixels for wing designs, scales may act as solar collectors to heat wing muscles, Davis suggests. "These insects have to raise their body temperature a certain amount before they can get their engines started in the morning," he says. That may explain why butterflies often appear to bask in the sun before flitting into the air.

The scales also serve a sacrificial role that enables butterflies and moths to get out of dangerous tangles. "When the insect hits a spiderweb, because its scales are loose, it can break free by shedding those scales," Eisner notes.


hether admired for their architectural intricacies or for their many varieties of chromatic splendor, lepidopteran wings evoke fascination and delight. As Eisner puts it, "They give us a sense of the beautiful."

For Sandved, the sense of beauty deepens with each new discovery of a human symbol in these wild but gentle beings. He laments that the rapid disappearance of many butterfly habitats will bar researchers from retracing the evolutionary paths that have led to such a spectacular diversity of designs.

For Ghiradella, the microstructural elegance of the scales demonstrates that lepidopteran beauty is more than a mere cover. And for anybody strolling in a mountain meadow, hiking through an Appalachian forest or sweltering in a tropical jungle, the fluttering creatures serve as public announcements that art abounds in nature. □