How Sustainable Engineering Solutions Depend on Biodiversity

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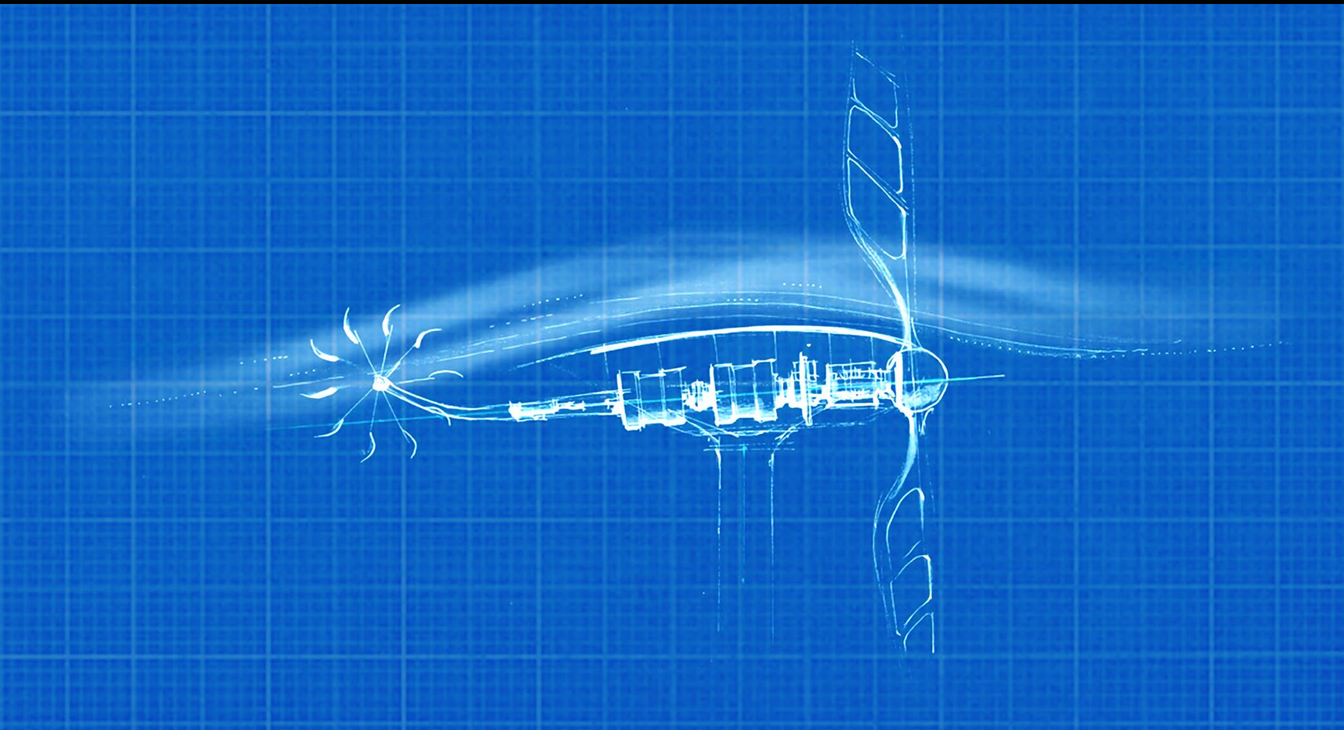

ABOUT THE AUTHORS

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◀ **COVER IMAGES** Photo of Emperor Dragonfly (*Anax imperator*), © Mark Carmody; Wind Turbine design for ENEL Green Power SpA, © Renzo Piano Building Workshop

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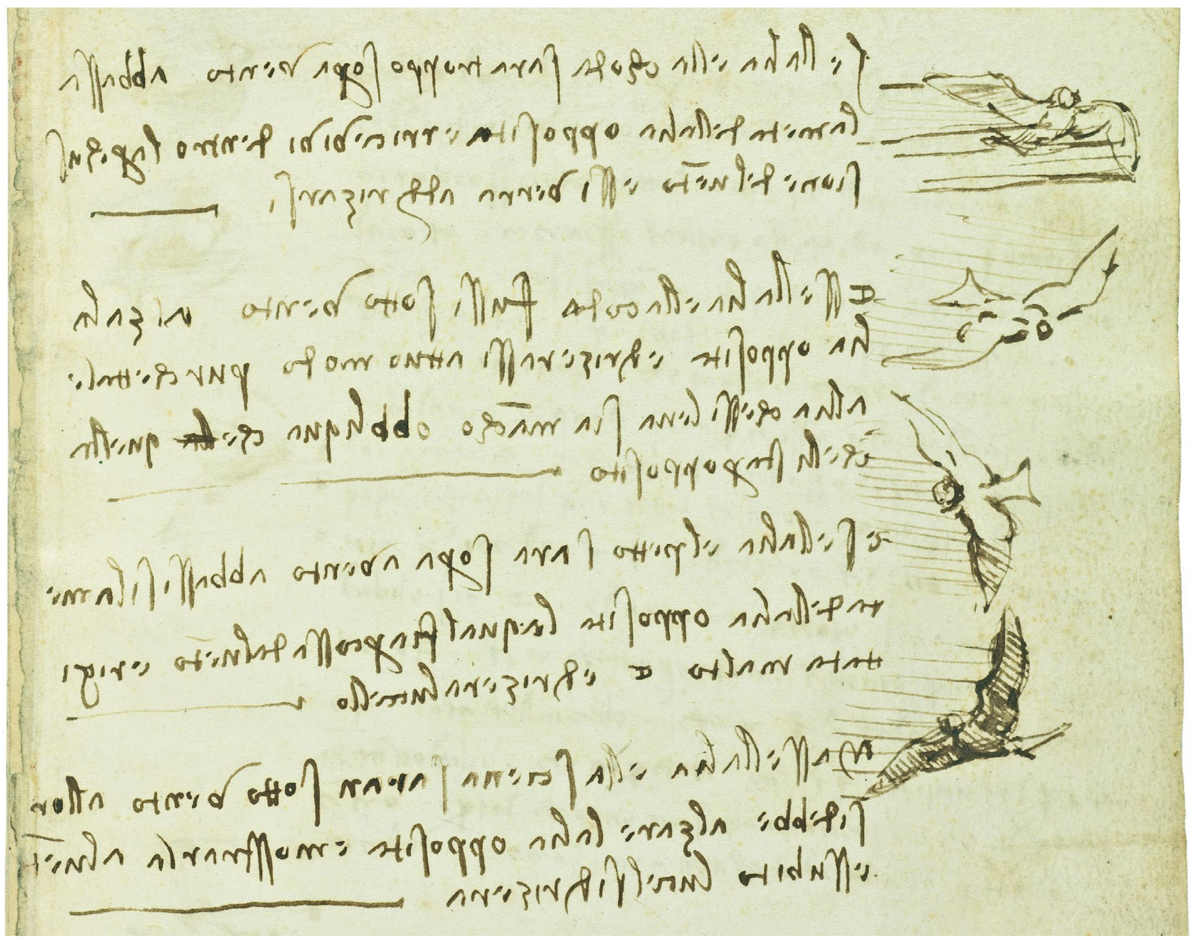
This booklet is dedicated to Edward O.Wilson, widely considered to be the "father of biodiversity." He has been an inspiration to the three of us - serving as a mentor, colleague, and dear friend. Of this project, he wrote the following:

> *"The argument they are making for preserving biodiversity, and in the process for protecting human health and life—by highlighting the engineering models that would be lost with a loss of biodiversity, each the product of natural selection, with the failed experiments no longer around—is an extremely powerful and highly unique one that should be given the widest possible attention."*
>
> \- Edward Osborne Wilson

"Human ingenuity will never devise an invention more beautiful, simpler, nor more to the purpose than nature does, because in her inventions nothing is lacking and nothing is superfluous."

- Leonardo da Vinci



▲ Studies of bird flight by Leonardo da Vinci. From the Codex on the Flight of Birds, Folio 8 recto. 1505-1506. United States public domain

Foreword

Life on Earth, at least 3.5 billion years old, is endangered by human activity as never before. Although we arrived only very recently on the planetary stage – just 300,000 years ago – our species, *Homo sapiens*, one among several million others, has had a profound and detrimental impact on life in all its forms. At least one million species are now threatened with extinction, according to the most comprehensive study on biodiversity ever conducted by the United Nations, released in May of 2019.

When a species goes extinct, it takes with it all of its unique properties, all of the physical, chemical, biological, and behavioral attributes that have been selected for that species, after having been tested and re-tested in countless experiments over many thousands, and perhaps millions, of years of evolution. It takes with it all its engineering secrets that it, and perhaps it alone, possesses--the anatomical and mechanical designs that keep it alive--designs for heating, cooling, and ventilation; for being able to move most effectively and efficiently through water or air; for producing and storing energy; for making the strongest, lightest, most biodegradable and recyclable materials; and for many, many other functions essential for life.

The engineering designs found in organisms living today are the ones that passed the tests, that were selected because they were more perfectly suited to the tasks they performed than competing designs, and often because they were more energy efficient and resource conserving. Those that failed, that did not meet these requirements, and the organisms that possessed them, are no longer around. They were out-competed by those that did. By this process of elimination, Nature has, in effect, done our engineering "field trials" for us.

Humanity faces unprecedented engineering challenges if it is to survive. By looking at a small sample of wondrous designs found in the living world, we intend to make a compelling case that solutions to these challenges are all around us, sustainable engineering models in plants, animals, and microbes waiting to be discovered. We hope that our work serves as a warning that we are in grave danger of losing these models, some perhaps forever, if we do not preserve the rich diversity of life on Earth.

In the pages that follow we will look at a number of organisms that have evolved unique anatomical and mechanical designs, sustainable engineering blueprints that hold important lessons for humanity.

While we will focus on the tragic fact that some of these organisms are threatened with extinction, or belong to groups of organisms that are, our main goal is to illuminate a small corner in the vast library of engineering designs found in the living world. If organisms we have identified and studied possess such extraordinary and critically important models, then what is there to be found in the great majority of organisms that haven't yet been studied, or in the multitudes that haven't even been identified? With a million or more species currently at risk of extinction, as physician Gro Haarlem Brundtland, former Director-General of the World Health Organization, once said about biodiversity, "the library of life is burning and we do not even know the titles of the books," much less what is in them.

Dragonflies & Micro-wind Turbines

Dragonflies may be Nature's oldest fliers, with fossils dating their origins back more than 300 million years. They may also be one of the best, demonstrating an aerial agility and efficiency unrivaled by any other organism. They can reach speeds of 40mph, take off vertically, fly straight up and down, and hover. They can also fly backwards, sideways, and upside down, and make instantaneous 180 degree turns that seem to defy the laws of inertia.

FIGURE 1 - MASTER FLIERS

An individual Globe Skimmer Dragonfly (*Pantala flavenscens*). © Rison Thumboor from Thrissur, India, CC BY 2.0

How could an insect with paper-thin wings achieve these aerial feats? When viewed from above, a dragonfly wing looks like a flat, stained glass window (Fig 2), but a side view reveals ridges and grooves. Scientists have discovered that this corrugated design allows the dragonfly's wings to be strong, stiff, and light, therefore requiring less energy to beat. As the wing moves through the air, the corrugations produce spinning masses of air, called vortices, that fill in the valleys between the wings' lateral ridges (Fig 3). These air vortices, operating like a line of miniature ball bearings effectively result in a "fluid-over-fluid" design, thereby 'lubricating' the wing. (In physics, both gases and liquids are considered to be fluids.) The air stream rarely touches the surface of the wing itself, reducing drag (air resistance) forces and improving energy efficiency. The vortices, particularly those at the leading edges of the wings, also generate lift, and, in effect, convert a corrugated surface into a smooth one so that the wings, aerodynamically, act as if they were a solid, cambered wing[1], further increasing lift for the dragonfly.

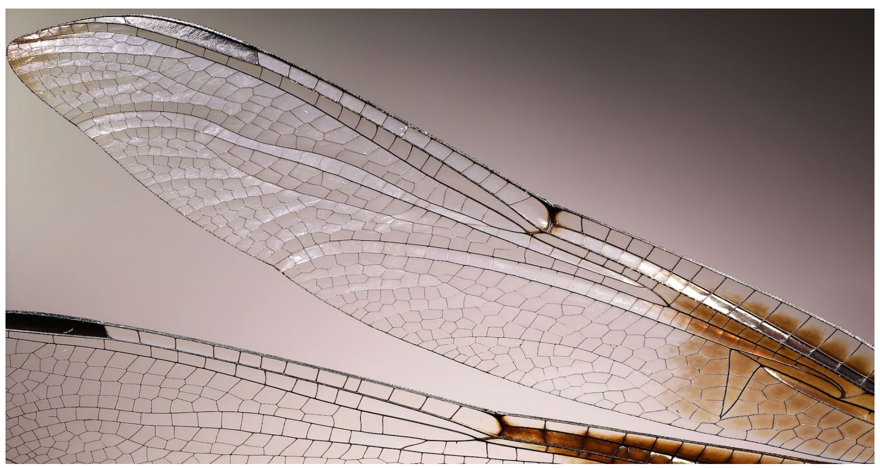


FIGURE 2
Photograph (using Helicon Software) of a dragonfly wing of the species *Libellula luctuosa*. See the ridges, formed by wing veins, and the deep valleys between them.
© Professor Brian Farrell, Harvard University

1. A cambered wing is one that in cross section has a more convex shape on its upper surface than on its lower.

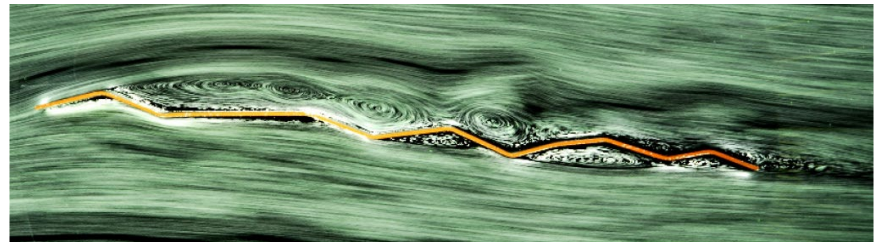


FIGURE 3
Model dragonfly wing in cross section in an air tunnel. Note the vortices of air in the valleys. © Professor Akira Obata, Micro Flying Robot Lab, Nippon Bunri University.

The overall structure of dragonfly wings has remained essentially unchanged, except in size, for over 300 million years, persisting from generation to generation, despite enormous shifts in global climatic conditions. Its specific corrugated wing structure has out-competed other designs at each evolutionary stage, suggesting that it must have met some very fundamental aerodynamic requirements, right from the start, that make possible the highly complex, acrobatic flight of dragonflies.

Perhaps this model of fluid over fluid flow is a more generalized phenomenon for organisms moving through air or water, one that could improve engineering designs by creating fluid interfaces that reduce both friction and the energy required.

Mitsubishi Heavy Industries has begun to employ this principle in its container ships, generating air bubbles that coat the under-water surface of its ship hulls (Fig 4), greatly reducing friction between the ship and seawater and improving its energy efficiency by 10-15%.

Inspired by the energy efficiency of dragonfly wings, particularly low wind speeds, Professor Akira Obata of Japan's Nippon Bunri University designed corrugated blades for micro-wind turbines (Fig 5) that turned, and generated electricity, at wind speeds as low as 2 mph. Most wind turbines perform poorly when speeds are less than 6 mph; some will not turn at all. By lowering the minimum wind speed requirements, these micro-wind turbines can harness wind energy in easily accessible locations like rooftops and balconies, and not need expensive towers to capture the higher speed winds found at higher elevations. By studying and understanding the aerodynamics of dragonfly flight, Obata was able to make inexpensive, light-weight, stable, and efficient micro-wind turbines that can be used in off-the-grid locations in developing countries.

FIGURE 4
The Mitsubishi Heavy Industries (MHI) Group's Air Lubrication System pumps air bubbles onto the bottom of a ship's hull to reduce friction. © Mitsubishi Shipbuilding

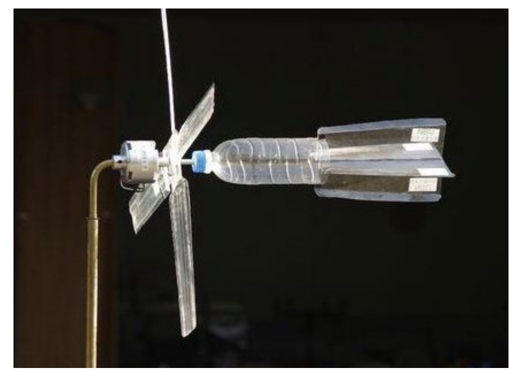


FIGURE 5
Micro Wind Turbine. Credit: Professor Akira Obata. © Micro Flying Robot Lab, Nippon Bunri University.

Tragically, an estimated 16% of the world's 6016 known species of dragonflies and damselflies are at risk of extinction, largely as their freshwater breeding grounds are deteriorating at an escalating rate—by pollution, by development and increased water demand, and by climate change.

Butterflies, Spiders, and Beetles

The Blackest Black and the Whitest White - Sunlight Absorption and Reflection

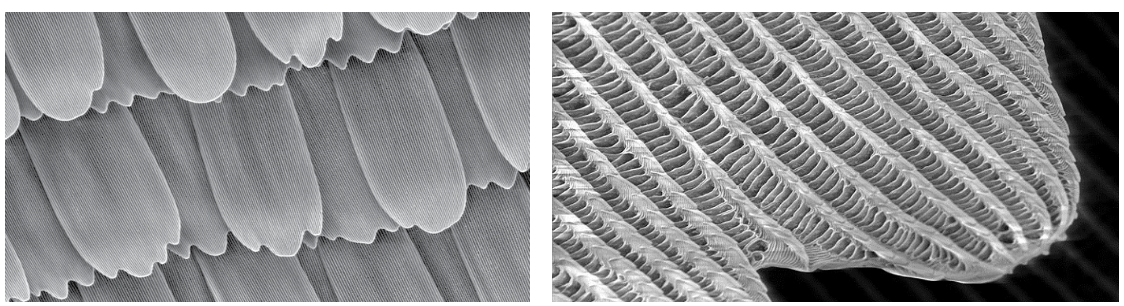
Some butterflies and other animal species may provide models for light absorption and light reflection that can be used for capturing and reflecting solar energy. It was originally thought that whether a surface maximally absorbed, or maximally reflected, sunlight was a matter of pigment alone - namely, how much and what kind of pigment was contained within it. But it is now clear that the micro- and nano-structures of surfaces[2] strongly determine their light absorptive or reflective properties. Understanding, not only the composition of the pigments involved, but also the fine-structure and the physics of these surfaces, may be useful in designing more energy efficient systems for heating and cooling buildings, and more productive solar energy collectors.

Some butterflies, birds, and spiders have evolved super black coloration achieved by a variety of complex light-trapping mechanisms that could lead to new energy-efficient designs for solar collection. In each case it is the combination of structural patterning at the micro- and nano-scale and pigments that results in extremely effective capture of light rays. The black portions of male Mountain Blue Don butterfly wings (Fig 6), for example, are made of arrays of overlapping rectangular scales, each composed of parallel ridges which are, in turn, connected by parallel ribs (Fig 7).

◀ **FIGURE 6 - BLACKEST BLACK**

The "blackest black" in a male Mountain Blue Don Butterfly *(Papillio ulysses ambiguous Rothschild).* © Notafly, CC BY-SA 3.0

This particular structure causes incoming light rays to be reflected many times within the wing scales, as if they were bounced like a ball in a closed box, rather than being reflected back out. With each internal reflection, some of the light rays are absorbed, especially when they reach the base of the scales, where the black pigment, melanin, is concentrated. As a result, there is maximum absorption of the visible light. Understanding how the fine structure of these scales contributes to light absorption may lead to the design of more powerful solar collection for heating and production of electricity. In fact, researchers have now fabricated thin, photovoltaic absorbers based on the fine structure of a related butterfly, *Pachliopta aristolochiae,* and have achieved increases in absorption efficiency of up to 90% for direct light, and up to 200% for indirect light (i.e. light entering at various angles with respect to the surface).



▲ **FIGURE 7** Mountain Blue Don Butterfly Wing Scales (magnified 200x and 5000x). © Tongxiang Fan

2. These are structures measured in microns, one millionth of a meter, and nanometers, one thousandth of a micron. A human hair is about 50 microns, or 50,000 nanometers, in diameter.

Butterflies are not alone in displaying these features. Other highly ornate groups of organisms have evolved super-efficient light traps (Fig 8). Birds-of-paradise, native to threatened jungle habitats of New Guinea and Australia, have dazzled people for generations with their extraordinary mating dances and almost glowing colors. Super black regions on their feathers multiply, scatter, and funnel light down into the feathers where it is absorbed by melanin pigment in its keratin, the same protein that makes up our hair and nails, causing as much as 99.95% absorption. Male peacock spiders also produce a super black color due to large numbers of micro-lenses that both focus light onto melanin pigments within the spider exoskeleton, and lengthen its path, thereby increasing how much light gets absorbed.

Researchers are now developing spider-inspired materials that could increase the efficiency of solar panels. Adding micro-lenses to the light-facing side of a solar cell, for example, can increase its light absorption efficiency by up to 10% compared to a flat surface. By mimicking the particular size and shape of spider microlenses, we may be able to achieve even higher gains in efficiency. Unlike many super black materials synthesized today, which are brittle and expensive to manufacture due to their nano-scale size, super black birds and spiders may also inspire cheaper, more durable pathways to highly effective solar collection that will work well in all weather conditions.

▲ **FIGURE 8** Bird of Paradise *(Lophorina superba)* © Edwin Scholes/Birds-of-Paradise Project; Peacock Spider *(Maratus karrie)* © Jürgen Otto; White Scarab Beetle *(Cyphochilus insulanus, Melolonthinae, Scarabaeidae)* © John Horstman; Small Cabbage White Butterfly *(Pieris rapae).* © Kathy Keatley Garvey

In contrast to 'blackest black' structures that maximize light absorption, some organisms have evolved 'whitest white' surfaces with mechanisms for scattering or reflecting light. The *Cyphochilus* beetle, for example, achieves remarkable whiteness with a highly disordered micro-scale structure, using the minimum amount of material for construction, one that scatters all wavelengths of light. This beetle's whiteness has already inspired ultra-thin, flexible, highly reflective polymer coatings that are ultra-white when dry, and transparent when wet.

Instead of scattering incoming rays, the white wings of the Small Cabbage White Butterfly (*Pieris rapae*) reflect light rays and put them to good use. Oriented in a V-shape, at a precise angle of 17 degrees, the wings concentrate and focus light, like a solar cooking oven, in order to warm flight muscles on cold cloudy days. When attached to a solar cell in the lab, and using the same orientation, these wings increased the cell's output power by over 40%.

With global climate change, cities have become significantly warmer than surrounding rural areas, because of the greater amount of heat generated and absorbed, a condition called the "urban heat island effect." The human health impacts can be extreme, with increased morbidity and mortality from heat stroke, air pollution, heart attacks, and pulmonary disease. The elderly, infants and children, and those with chronic heart and lung diseases are the most vulnerable. Much attention has been paid to installing white roofs on city buildings to make them more light-reflecting, thereby reducing temperatures inside the buildings, and cumulatively, reducing temperatures in cities. If we used paints modeled after surfaces like those of the *Cyphochilus* beetle or Small Cabbage White Butterfly, we might achieve significantly greater cooling.

Fog-Harvesting Beetles

Hydrophobic Surfaces, Water Capture and Flow

The Namib desert, running along the coast of South-West Africa, is one of the driest places on Earth, and yet is home to the world's largest number of desert species found nowhere else. Plants, animals, and microbes that live in the Namib have evolved unique structures, mechanisms, and behaviors to survive the extreme drought, high temperatures, and lack of food. Much of the desert averages less than one inch of rainfall per year, posing an enormous challenge for life in the Namib. But there is another source of water that has been an essential source of life for many desert-dwelling organisms - the dense blankets of fog that develop offshore and drift eastward across the desert. Among these organisms, two species of beetles, *Onymacris unguicularis* and *Onymacris bicolor*, actively harvest water from fog with a sequence of behaviors called "Fog Basking" (Fig 9). Late at night, in advance of the fog, the beetles emerge from the sand and climb up the dunes to place themselves in the fog's path. Tilting their bodies forward while facing the fog, they harvest moisture on their backs, which are made of hardened forewings called elytra that cover and protect their hind wings, used for flying. The small water droplets in the fog collect there, coalesce to form larger droplets, which, by the force of gravity, run down the smooth hydrophobic (i.e. water-repelling) surfaces to the beetles' mouths.

FIGURE 9 - FOG HARVESTING BEETLE

Onymacris unquicularis with 'fog-harvested' water droplet at its mouth. © Martin Harvey, www.wildimagesonline.com

The specific chemistry and structure of hydrophobic surfaces found in Namib beetles has generated enormous scientific interest for their potential human applications. There is growing recognition that similar materials - including superhydrophobic surfaces (where water tends to bead up even more dramatically) - are ubiquitous in Nature. We see examples of this in some plants with self-cleaning superhydrophobic surfaces, where rain can more easily remove surface dirt that otherwise would interfere with photosynthesis; some insects where dust, that would make flight difficult, is similarly removed from their wings and other body surfaces (Fig 10); some aquatic organisms like water-striders, that can glide on the water's surface because their feet have superhydrophobic soles; some aquatic birds, which can then shed water so that they are able to take off; and countless other organisms.

Incorporating such properties into new materials holds enormous potential for sustainable engineering designs - from harvesting water from fog for human populations (Fig 11), to making use of their self-cleaning properties, cooling computers, condensing water for power and desalination plants, and even coating ship hulls with superhydrophobic materials to lubricate their passage through water, thereby increasing fuel efficiency.

The WHO estimates that half the world's population will live in water-stressed areas by 2025, a proportion likely to grow significantly with climate change and increased populations. Harvesting water from fog will help provide water for drinking and for agriculture in some coastal and mountainous areas. By coating the nets of fog-harvesting systems with hydrophobic surfaces, water capture and flow may be greatly increased.

With humanity's ever-increasing computing needs, overheating of microchips has also been a growing problem resulting in chip malfunction or permanent damage. New research on super-hydrophobic surfaces applied to computer chip microchannels suggests that the resulting increased flow of cooling liquids in these channels can greatly improve cooling efficiency.

FIGURE 10 A Dragonfly coated by nearly-spherical water droplets, a sign of a superhydrophobic surface. © David Chambon

Using superhydrophobic surfaces to improve water condensation has the potential, not only to markedly decrease greenhouse gas emissions in steam-generating power plants run by fossil fuels, but also to increase energy efficiency in air conditioners and dehumidifiers, and in the production of fresh water, not from fog, but from the most unlimited water source of all - seawater. As in steam-generating power plants, superhydrophobic surfaces can greatly increase the energy efficiency of this process.

The massive decline of insect populations in recent years is true for beetles as well, with large numbers threatened with extinction. At least fifteen species have gone extinct, a number that is most likely a vast underestimate given the difficulty of establishing these losses with the dimensions of the populations involved. These losses and threatened losses have alarmed the scientific world, as insects perform essential ecosystem services that support all life on Earth. Considering that only two species of beetles from the Namib desert have helped stimulate research in a wide variety of areas that have critically important implications for sustainable engineering design, one has to wonder what other secrets are being lost every day from the extinction of other beetles, and from other insects in general, increasingly threatened by human activity.

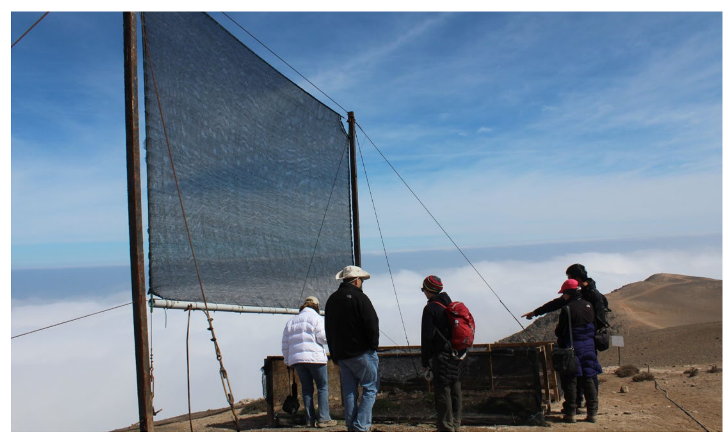


FIGURE 11
Nets to capture coastal fog in Alto Patache, Atacama Desert, Chile.
© Pontificia Universidad Católica de Chile, CC BY-SA 2.0

Owls & Silent Wind Turbines

Owls have evolved silent flight to become master night hunters. By minimizing noise generated by their wings, they not only avoid being detected by their prey, but also enhance their ability to detect their prey's movements.

There are four features that together contribute to the silent flight of owls. First, they have very large wing spans compared to their body lengths and to the chord (the width) of their wings. As a result, they can fly or glide at low speeds and generate less wing tip turbulence during flight, both of which reduce sound levels.

FIGURE 12
SILENT FLIERS

Barn Owl *(Tyto alba).*
© Ron Dudley

Second, the stiff, comb-like feathers along their wings' leading edges (Fig 13) break up the air flowing over them into small air vortices that generate lift, which is maintained even at steep wing angles (the angle a wing makes with the airstream is called "the angle of attack"). To slow down and land in order to capture its prey, a flying owl needs to stall by flying at a steep angle of attack. While other flying animals (and planes and other flying objects) generate noisy turbulent airflow when stalling in flight, the owl's comb-like feathers muffle this noise at the most important time for the owl, enabling it to silently grab its prey with its talons.

Third, their wings' primary flight feathers are covered on their upper sides by soft, velvet-like downy material that absorbs sound, particularly sounds at higher frequencies that most prey hear the best.

Finally, the feathers along the trailing edges of the wings, where the most noise is generated during flight, are composed of a very fine, flexible fringe that breaks up the air flow still further, resulting in additional noise reduction.

Despite a great deal of public support in many countries for wind energy, and a rapid growth in the number of wind farms around the world, the placement of wind turbines on land has often been met with great resistance. While there is still some controversy about whether or not proximity to a wind energy farm directly affects human health, many have opposed wind farms in their communities because of the noise they make, particularly at night. There are also concerns about the variations in air pressure levels that are created, which, while not audible, can result in such effects as windows rattling in their frames.

To respond to these concerns, the Siemens-Gamesa Corporation, after many years of studying the structure and aerodynamics of owl wing feathers, developed a wind turbine blade called DinoTail® (Fig 14) that significantly reduces sound levels at all wind speeds. They copied the comb-like leading wing feathers found in owls, as well as the fringe-like structures of trailing edge feathers, combining them at the trailing edge of their turbine blades.

There is an additional benefit in these owl-feather-inspired blades. Unlike turbines on land that need to be slowed down by braking to reduce ambient noise levels, quieter blades, like those of DinoTail® wing turbines, can remain at speed, resulting in greater energy production.

FIGURE 13
Comb-like leading edge of Barn Owl feather.
© Kay Schultz

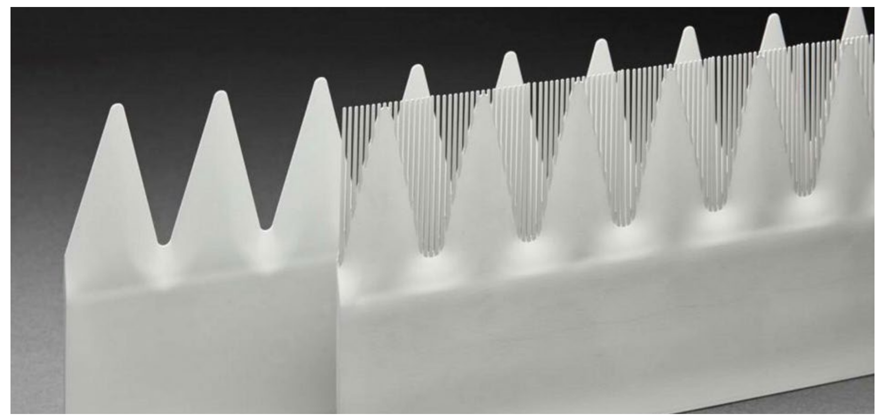


FIGURE 14
Siemens-Gamesa Corporation DinoTails® Next Generation Owl-Inspired Wind Turbine Blade Trailing Edge.

The Ziehl-Abegg Company, a German engineering company, has also studied the structure of owl feathers to develop quiet, highly energy efficient fans that move large volumes of air for ventilation and air conditioning. These fans mimic the comb-like structure of the feathers at the leading edge of owl wings.

There are about 200 species of owls, found everywhere on Earth except polar ice caps and on some islands. Of this number, four have already gone extinct, and some thirty-four are threatened with extinction, six of which are critically endangered. While the remaining owl species are not considered threatened at this time, a steady decrease in owl populations, along with numerous other bird species as well, is cause for great concern.

There are several reasons for these declines. Many owls depend on intact forests that are dwindling with the rapid global increase of deforestation. Owls are also threatened by loss of their traditional habitat by farms and development, by being exposed to insecticides (as many species prey on insects), by viral diseases (including that caused by West Nile Virus), and by poaching.

Gliding and Soaring Birds
How They Have Taught Us to Fly

For hundreds of years birds have been models for human efforts to fly - from the Renaissance sketches of Leonardo Da Vinci, and Otto Lilienthal's pioneering 1890's work on gliders inspired by storks, to the Wright Brothers' 'wing warping' concepts in the early 20th century based on Etienne-Jules Marey's highspeed photographs of bird flight. The study of gliding and soaring birds has continued to provide aeronautical engineers with innovative design concepts to improve the efficiency of flight.Perhaps the most dramatic, recent example is the widespread adoption of "winglets,"the upward bend added at the tip of wings in almost every modern plane (Fig 15, left panel) that was inspired by the upturned wingtips birds display while gliding and soaring.

▲ **FIGURE 15** On the left, a modern plane winglet. © PierreSelim, CC BY-SA 3.0
On the right, wingtip vortices in the wake of a plane without winglets. © Steve Morris

When a plane (or for that matter, a bird, a bat, or an insect) is flying, air pressures along the bottom of its wings are greater than they are at the top, lifting the plane (or the animal) against the force of gravity. Air streams below the wing also push upward and outward, and curl around the wings' trailing edges. There they meet the lower pressure air streams flowing over the top of the wings and curving inward toward the body of the plane. These colliding air streams produce spinning currents called vortices, which move to the wingtips and combine to form larger, swirling masses of air that resemble small tornadoes. These wingtip vortices reduce air pressure behind the plane, and increase drag forces, particularly during take-off and landing. As a consequence, the plane slows down or sacrifices altitude, lift is reduced, and greater amounts of fuel must be used for flight to be sustained.

> *"Learning the secret of flight from a bird was a good deal like learning the secret of magic from a magician."*
>
> \- Orville Wright

Engineers have long known that one can decrease the impact of air vortices at a plane's wingtips, thereby decreasing drag, by increasing the length of its wings (a feature found in soaring birds like the Albatross – see Fig 17). However increasing the length of wings for commercial airplanes involves unacceptable trade-offs, as planes with very long wings require additional structural support and would therefore be heavier and less energy efficient. The more successful bio-inspired solution, noticed and developed by NASA aeronautical engineer Richard T. Whitcomb, was to equip wings with winglets. Indeed, he reasoned that if planes had upturned wingtips, similar to those seen in gliding and soaring birds, they would have greater fuel economy. He determined that winglets not only reduced wingtip vortices and drag, by preventing some of the higher pressure air currents from the bottom of the wings from flowing around the wingtips to the top, but also lowered planes' noise footprints by more than 6%.

Whitcomb's invention has revolutionized modern aviation. His initial prediction that winglets would result in greater fuel economy was realized beyond his dreams: it is estimated that the most recent winglet designs have saved commercial and business jet operators globally more than 10 billion gallons of fuel, while reducing their CO_2 emissions by 105 million tons. To understand the enormous scale of these reductions, consider that saving 10 billion gallons of fuel is the approximate equivalent of taking more than 20 million U.S. cars off the road for a year. And that reducing CO_2 emissions by 105 million tons a year would require planting about 40 million acres of trees.

◀ **FIGURE 16 - WING DESIGN**

On the left, the Turkey Vulture (*Carthartes aura*) displays 'slotted wingtips.' © Peterwchen, CC BY-SA 4.0

On the right top, the Peregrine Falcon (*Falco peregrinus*) in a high speed dive (called a "stoop"). © Rob Palmer, rob@falconphotos.com

On the right bottom, the Common Swift (*Apus apus*) displays wing morphing while flying at high-speeds. © Francesco Veronesi from Italy, CC BY-SA 2.0

Further study of wingtip feathers in gliding birds like vultures (Fig 16), eagles, storks, cranes, herons, and hawks has revealed additional design features to be mimicked in airplane wings. Indeed these birds are capable of gliding and soaring for long periods of time with little expenditure of energy because their wingtip feathers spread apart from each other and turn upwards during flight. In this configuration, each wingtip feather behaves like a small winglet, which, acting together, break up the overall "wingtip vortex" thereby reducing its effective strength and the amount of drag produced. Although no planes have yet been built with these kinds of 'slotted' wingtips, there are many studies now in progress, designed, not only to harness the benefits of such features, but also to expand the ability of plane wings to move and change their shapes and surface areas, as birds do.

Two birds capable of changing the shapes and surface areas of their wings, a process called "wing morphing," are being studied as airplane models - the Peregrine Falcon (*Falco peregrinus*) and the Common Swift (*Apus apus)* (Fig 16). The Peregrine Falcon, a crow-sized predator, is able to fly at speeds of more than 200 miles per hour, making it the fastest bird, in fact, the fastest animal on Earth. It spends much of its time gliding with outstretched wings, but when hunting, it folds its wings, diving for its prey at high speed. It is an important wing-morphing model, not only because of its ultrahigh speed flight, but because, despite these speeds, it still has superior maneuverability, and its wings are capable of withstanding extreme forces.

The Common Swift can stay aloft for 10 months at a time—eating, drinking, mating, even sleeping, while flying more than 500 miles a day. During its lifetime, it may fly as much as 2.8 million miles! It is able to glide for very long distances at 20 miles per hour, rarely flapping its outstretched wings, but when hunting, it sweeps its pointed wings back into a double, curved-blade sickle shape and flies at speeds that approach 70 miles per hour, the highest speeds known for any bird in level flight, and can make sharp turns at these speeds without damaging its wings. No wonder it has been a model for some fighter jets, like the U.S. Air Force F-1 Tomcat, which, however, do not come close to the supremely acrobatic, energy efficient flight of the Common Swift.

Albatross species (Fig 17) have also been a model for new airplanes. They may be the most energy efficient travelers of any vertebrate on Earth. They are able to soar for several hundred miles a day without flapping their long, thin pointed wings, and have been known to travel up to 75,000 miles a year. They do this by making use of the differences in wind speeds that exist at different levels above the ocean's surface, and by upwelling air deflected by the slopes of large waves. Airbus has built a a highly energy efficient experimental plane model "Albatross One" that has long, thin, pointed wings with hinged wingtips, patterned after the Albatross.

There are many migrating wild geese, pelicans, ibises, swans, cormorants, and ducks that fly in V-formations (Fig 18). Studies have shown that this pattern leads to highly energy efficient flight, with birds in the V making use of the up-welling air currents generated by the wing-tip vortices of the birds in front of them. It is thought that commercial passenger jets could reduce their fuel consumption and CO_2 emissions by 5-10% if they mimicked migrating birds by travelling in V-formations.

◀ **FIGURE 17**
Wandering Albatross
(Diomedea exulans).
© Gary & Donna Brewer

FIGURE 18 ▶
Snow Geese
(Anser caerulescens)
flying in V-formation.
© Jeannie Park

Birds taught us how to fly. And they are continuing to teach us, not only how to improve our flight performance, but how we can fly with the greatest energy efficiency - using the least amount of fuel and emitting the fewest greenhouse gases. And yet we are losing bird species at an unprecedented rate, including albatrosses, eagles, vultures, cranes, ibises, herons, hawks, and others that have evolved unique engineering models for energy efficient flight. Many of them are critically endangered, only one step removed from extinction. Human activity, including climate change, threatens birds in many ways. But perhaps the human behavior that is most threatening for birds is the habitat modification and destruction from intensive, industrial-scale agriculture, coupled with the often indiscriminate, landscape-wide application of pesticides that has also been linked to the collapse of insect populations in recent years. As insects are a primary food source for many birds, when their populations decline, so do those of many birds.

In 1962, Rachel Carson published *Silent Spring*, warning the world about the lethal effects of DDT on some birds. These warnings were largely heeded, and birds like the Peregrine Falcon, which had been threatened with extinction because of DDT, recovered. She would be horrified, and distraught beyond measure, to see what humanity is now doing to insects and birds.

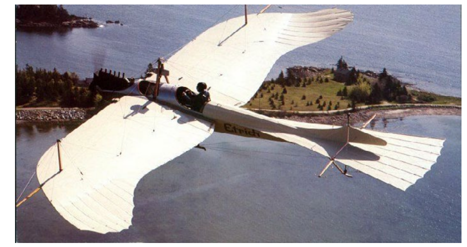
Airborne Seeds

New Models for Capturing Wind Energy?

In addition to studying master fliers that can launch themselves and actively fly with their wingbeats, there is much to learn from organisms that exclusively glide, incapable of staying aloft by their own power. They rely instead on unique structures (and in some gliding animals, how they position them) to generate enough lift to slow their descent as they are pulled back to the Earth by gravity.

In the plant world, several aerodynamic designs for gliding have evolved in seeds for the purposes of being carried beyond the area of shade cast by the parent plant. This increases their chances of survival by colonizing new environments, with improved conditions for germination, healthy growth, and eventual reproduction. In studying airborne seed designs and how their fixed structures generate lift without any energy expenditure, we may discover important new models for how to harness the wind to generate electricity.

◀ **FIGURE 19**
Javan Cucumber
Samara
(Alsomitra
macrocarpa).
© Scott Zona



◀ **FIGURE 20**
Etrich-Taube
Airplane.
© Alchetron

There are many types of gliding plant seeds, some of which are referred to as "winged seeds" or "samaras." Each type of samara may employ a different aerodynamic design. The Javan Cucumber *(Alsomitra macrocarpa)* (Fig 19) is a prime example of a simple glider that has figured prominently in the history of human flight. Released from gourds from the treetops of tropical forests in Southeast Asia, Australia, and South America, these samaras have wings made of extremely thin, but durable membranes with a wingspan of six inches or more, and sharp wing leading edges that enable high lift-to-drag ratios.

Their unique structure enables stable flight. For one, the seed sits at the center of gravity, and the wings curve upwards, with their tips above the level of the samara's center. In addition, the wings are swept back and have trailing edges that are tipped slightly upwards, which, together, help prevent pitching up and losing control. These structures together give the Javan Cucumber samaras remarkable stability, allowing them to resume gliding after being hit by wind gusts, and even after collisions, common in the high canopy of the forest.

This design served as a model for the Austrian aeronautical engineers, Ignaz "Igo" Etrich and Franz Xaver Wels who built a successful unpowered glider in 1904, followed by a powered one in 1908 called the Etrich-Wells Tailless parasol. Two years later, Etrich added a bird-like tail and built the Etrich Taube (Fig 20), a stable, propeller plane - the first to fly at high altitudes and to become a mass-produced military airplane, one that was widely used by Germany during World War I.

Unlike the still and steady gliding of the Javan Cucumber samara, Maple samaras (found in Asia, Europe, North Africa, and North America) auto-gyrate, or twirl in a helical pattern, generating lift that slows their descent by turning around a vertical axis of rotation, with the seed at the center of gravity. Their weights and shapes result in angles and speeds of rotation where all forces balance, making them inherently stable (Fig 21). While the blunt-shaped, heavy seed produces little or no lift as it falls, the Maple samara wing generates leading-edge vortices and powerful lift forces as it rotates, pushing the wingtip upwards and inwards towards the axis of rotation. This inward (centripetal) force is balanced by the outward (centrifugal) force created by the rotation. In addition, the auto-gyrating seed, like a

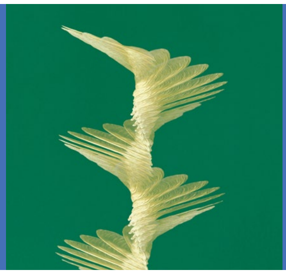


FIGURE 21
Timelapse of a Maple Seed Flight Path.
© David Lentink, University of Groningen

FIGURE 22
A Vertical Axis Wind Turbine (a helical Darrieus-type turbine).
© Alamy

spinning top, becomes a gyroscope as it falls, thereby resisting any change in the angle formed with the axis of rotation, resulting in even greater stability. Although the rotation of Maple seeds only slows their vertical descent, it creates greater opportunities for them to be dispersed by the wind.

The scientific research of David Lentink and his co-workers at Wageningen University and the California Institute of Technology on the powerful leading-edge vortices of Maple samaras has helped engineers apply this auto-gyrating model to vertical-axis wind turbines (VAWTs) (Fig 22). What makes Maple samaras of great interest as models for VAWT design is that they have very high “power coefficients” (i.e. very high efficiency in turning the wind energy flowing through them into mechanical power). In fact, the power coefficients of some Maple samaras are higher than those of most wind turbines in use today, and are close to the limit of what has been thought to be possible.

New innovations in VAWT designs have proven to be highly energy efficient, and more effective for some applications than Horizontal Axis Wind Turbines (HAWTs), where the axis of rotation points into the wind. VAWTs are, in general, smaller; cheaper; and easier to build, transport, and install. They are also less dangerous to maintain than HAWTs. VAWTs can be effective in a wide range environments by producing power regardless of the wind’s direction and by being effective at both low and turbulent wind conditions. In particular, the use of VAWTs in urban settings would decrease the loss of electrical power that occurs when it is transferred from the point of generation to the final destination, a problem that occurs with long transmission lines, where losses can reach levels of 8-15%.

Tree of Heaven *(Alianthus altissima)* samaras have evolved a different mechanism for distancing themselves from their mother tree (Fig 23). As they fall, Tree of Heaven samaras spin about their long axis, perhaps initiated by the corkscrew shape, with the axis remaining parallel to the ground. Since the side of the seed rotating upward and away from the ground follows the same direction of the upward airflow around the seed as it falls, the airflow on this side moves faster and, therefore, has lower air pressure than the airflow on the side of the seed rotating toward the ground. This causes the seed to deflect sideways towards the low pressure side, a phenomenon called the Magnus Effect, one that is seen when there are similar pressure differences with curve ball pitches in baseball and with golf balls that are spinning.

Engineers at the Tokyo-based company, Challenergy, Inc. have used the Magnus Effect to create a VAWT with motorized, rotating cylinders that increase the overall rotational speed of the turbine. This design results in turbines that can harvest wind energy from any direction and that continue to function even under very high, typhoon-level wind conditions (Fig 24).

FIGURE 23
Tree of Heaven Samara *(Alianthus altissima)*.
© Jeff Hansen, www.kansasnativeplants.com

FIGURE 24
Magnus-Effect-Exploiting Turbine Design.
© Challenergy Inc.

Fibonacci Numbers and Fractals in Plants

New Models for Solar Power?

Fundamental physical laws dictate how all matter behaves - laws, as Euclid said more than 2300 years ago, that can be written in the language of mathematics. The shapes and patterns we observe over and over in living organisms, that are determined by these physical laws, evolve over time, refined by the countless trials of natural selection. Two such mathematical patterns, both found in plants, are of particular interest as the basis and inspiration for sustainable engineering designs: the Fibonacci Sequence and Fractals.

The Fibonacci Sequence, in which each number is derived by adding together the two consecutive numbers preceding it (i.e. starting with zero: 0, 1, 1, 2, 3, 5, 8, 13, 21, 34, 55, 89, 144, 233, 377, 610, etc.) is ubiquitous in nature. We find it in the patterns formed by sunflower seeds, in the arrangement of pinecone scales, in the patterned array of leaves from succulent plants, as well as in the number of petals and florets found in many flowers. Embedded within the Fibonacci Sequence is the Golden Ratio (represented mathematically by the formula $(\sqrt{5}+1)/2$) and approximated by dividing any number in the Fibonacci sequence (starting with 3, the 5th number) with the number preceding it. Furthermore, if one divides a circle of 360 degrees by the Golden Ratio, one produces a portion of the circle having an angle of approximately 222.5 degrees, the remainder of which is called the Golden Angle (approximately 137.5 degrees). This is one of the most common angles in all of Nature, widely found for example in the angles that separate the leaves of most vascular plants, and of some non-vascular plants like mosses, as they form around a stem.

▲ **FIGURE 25 - FIBONACCI SEQUENCE** On the left, a sunflower seed head in which the number of clockwise and counterclockwise spirals correspond to Fibonacci numbers. © Esdras Calderan from Santos, SP, Brazil, CC BY 2.0. On the right, an aerial view of the Planta Solar 10 and 20 (PS 10 and PS20) solar thermal power plant in Andalusia, Spain. If their reflecting mirrors had been reconfigured into Fibonacci spirals, PS10 and PS20 could have held approximately 20% more mirrors in the same area. © Koza1983, CC BY 3.0

Although the study of the patterns that leaves make as they grow is an ancient science dating back at least to the Greeks, it was not until the 1750s that detailed observations of leaf spacing were undertaken and linked to plant fitness. It was eventually proposed that this angle of separation not only helped prevent leaves from blocking each other from a free circulation of air, but also that this arrangement maximizes both their capture of light and photosynthetic activity. While the physical and developmental reasons that explain how such structures are generated is a fascinating topic in its own right, for our purposes it is most important to notice that these patterns lead to efficient packing arrangements – ones that have profound implications for several human engineering challenges. For example, the conversion of sunlight into energy in solar thermal power plants (where energy from the sun is reflected by vast arrays of parabolic mirrors to a central tower where it is concentrated to produce steam that drives turbines and generates electricity) can be optimized by spacing and orienting the numerous mirrors. Employing Fibonacci spirals not only makes it possible to pack more mirrors in the same amount of space (20% more), but by angling each mirror relative to its neighbor by the Golden Angle reduces the amount each is shaded from the sun, and each is blocked in its reflection back to the tower, by those in front of it. Similarly, "Solar Trees" that array photovoltaic panels according to Fibonacci-based spacings produce 11% more voltage and 25% more power than flat-oriented models with the same footprint.

Like the Fibonacci sequence, fractals (characterized by geometrically identical patterns that recur at progressively smaller scales), are found everywhere in the natural world - from the capillaries and air channels in our lungs to the veins of a leaf (Figure 26). Natural selection favors these patterns in living things, as such branching into smaller and smaller units maximizes the surface areas per unit volume for the exchange of gases, fluids, and messages (both chemical and electrical), while minimizing the times and distances required for such exchanges to occur.

▲ **FIGURE 26** On the left, the veins of a leaf display fractal repeating patterns at different scales. © CatDancing, Flickr. On the right, a Romanesco Cauliflower that presents both fractal and Fibonacci patterns. © Ivar Leidus CC BY-SA 4.0

Such packing efficiencies have numerous applications in sustainable engineering practices. The ability to harvest and store solar power with maximum efficiency has long been an important goal, and super-capacitors have been considered leading candidates for this kind of application. Unlike conventional batteries that store electrical energy chemically, super-capacitors store it in electric fields, allowing them not only to charge and discharge more rapidly, but also to last much longer, being re-chargeable essentially without limit. However, because of their planar design, super-capacitors have not been able to store sufficient energy to make them effective solar batteries. By mimicking intricate, fractal-like designs, researchers have produced flexible, porous, highly conductive, solar-energy-capture electrodes, which maximize surface area per unit volume and minimize ionic path distances. When linked to super-capacitors, these electrodes produced electrical densities (the amount of electrical energy stored per unit volume) that were 3000% greater than those produced by conventional solar energy systems.

These very powerful, highly-efficient solar energy devices have countless potential applications—from smart phones to laptops, from placing them on the rooftops of hybrid and electric cars to attaching them to the windows of buildings. They could also be made portable and wearable. Were it not for the observations of organisms that display and benefit from such fractal-like designs, these devices might never have been invented.

Humpback Whales

Wind Turbine Blades and Fans

Although most often thought of as slow moving and clumsy, Humpback Whales (*Megaptera novae-angliaea)* may be the greatest acrobats of any marine animal for their size and weight. Scientists have observed Humpbacks during group hunting and have discovered that they can maneuver with faster, sharper turns than engineers thought were physically possible. How exactly do these mammoth creatures produce the enormous amounts of lift required for their extraordinary maneuverability, while minimizing drag that resists their movement through the water? New insights have led to improved wing designs for more sustainable applications in airplanes and wind turbines, and for innumerable devices that incorporate fans.

◀ **FIGURE 27**
ACROBATIC GIANT

On the left, Humpback Whale. © Vanessa Mignon

On the right, tubercles on the leading edge of a Humpback Whale flipper. © William Rossiter

In addition to the Humpback Whales' enormously flexible spines and huge powerful tails, the secret to their agility is thought to lie with their pectoral flippers, the largest appendage of any animal on Earth. They display how powerful and effective their flippers are during coordinated group hunts called "bubble-net feeding" in which different whales play different roles. Some produce a cylinder of bubbles to corral a school of fish, as the fish will not swim through the bubbles. Others dive below the school and force it up into the cylinder. When the fish are fully trapped, all the whales swim to the surface within the cylinder and swallow their prey. In this highly choreographed hunting behavior, these 50-foot, 30-ton animals are able to make very tight turns in the water, banking at sharp angles and at high speeds.

The secret of how Humback Whales maintain speed at such extreme angles may lie in the shape of the flippers themselves. Along the flippers' leading edges, there are rounded swellings called tubercles arranged at regular intervals, giving them a scalloped appearance (Fig 27). Like albatross wings, Humpback flippers are tapered at their tips and are also proportionally very long and thin, giving them very high "aspect ratios." These structures allow them to generate large lift forces with minimal drag, making them highly efficient swimmers. But more notably, scientists have found that they are able to stay in motion longer while turning at sharper angles than many other winged creatures. In other words, Humpback Whales achieve notably high angles of attack in the water without stalling.

To understand lift and drag, we can consider the simpler airplane wing model (Fig 28). By tilting the leading edges of its wings upwards, the angle of attack increases, creating a pressure differential: less pressure above the leading edge which generates lift. In addition, at the trailing edge, the air is pushed down and hence, by Newton's 3rd Law (for every action, there is an equal and opposite reaction), the wing is pushed up. One might simply conclude, the greater the angle of attack, the more the lift – thus, goal achieved. However, if the angle of attack continues to increase beyond a certain critical angle, airflow over the upper surface becomes highly unstable, with the formation of strong vortices that dramatically reduce lift while increasing drag, causing the plane to slow down and stall, essentially "falling out of flight" (Fig 29).

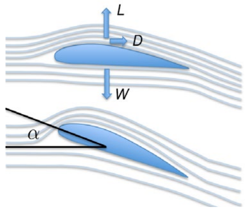


FIGURE 28
Airflow for Airplane Wing

(L=lift, D=drag, W=weight, α = angle of attack)

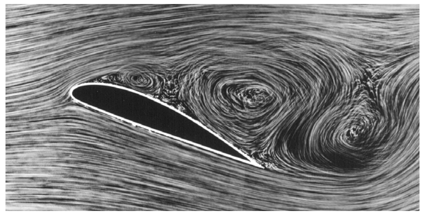


FIGURE 29
Airflow at High Angle of Attack with Vortices Causing Stall.

But while airplanes stall when their angles of attack exceed 15-20 degrees, Humpback Whale flippers can reach angles of 25 degrees or more without stalling, allowing them to generate enormously powerful lift forces without associated drag. For more than a decade, marine biology professor Frank E. Fish of West Chester University, and his colleagues at Duke University and the U.S. Naval Academy, have been studying just how whales achieve this feat. They have found that the tubercles on the leading edge of the flippers generate a pair of counter-rotating vortices within the valleys between them that decrease pressures over the tops of the flippers. These vortices also accelerate water flow over the flipper, pushing back water turbulence that develops with increased angles of attack towards the trailing edges. In addition, the valley vortices prevent "spanwise" water flow, that is, flow from the Humpback's body, where the flipper attaches, to its tip, thereby decreasing flipper tip vortices. Taken together, these effects increase lift and decrease drag at high angles of attack, preventing stalling. (Fig 30).

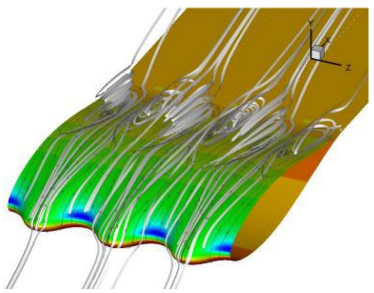


FIGURE 30
Model of water flow over a short cross-section of the tubercles (lower left of the image) on the leading-edge of a Humpback Whale flipper.

In recent years, many sustainable engineering applications have been inspired by Humpback Whales. The WhalePower Corporation, founded by Professor Fish, Dr. Philip Watts, Bill Bateman, and Stephen Dewar, originally developed and patented "Humpback Whale Technology," the use of tubercle-like projections on the leading edges of rotating blades. In partnership with Envira North Systems for manufacturing and distribution, WhalePower Corporation has brought the Axiom fan to market - a 10-foot diameter industrial fan that is 20% more efficient and, due to lower stress forces, has a lifetime that is 25% longer than conventional fans its size. The WhalePower Corporation has also developed tubercle-blade micro-fans to cool computers and other electronic devices that are 20% more energy efficient than conventionally-designed computer fans.

But their most significant sustainable engineering development has been wind-turbine blades. Traditional Horizontal Axis wind turbines designs have become taller and taller to reach the faster, steadier winds present at higher altitudes. Some are over 800 feet tall. But to avoid damage, as winds can still be turbulent and change abruptly, these turbines are made heavier, and with reduced angles that the blades form with the wind's direction, both of which compromise performance.

WhalePower Corporation has proven that by mimicking leading edge tubercle design of whale flippers, they can harvest wind energy more efficiently under a wider range of wind conditions, improving annualized production by some 20%. The turbines are also more stable, durable, and quieter than traditional ones.

As with organisms on land, many marine species are in great danger. Coastal ecosystems—coral reefs, mangroves, estuaries, salt-water marshes, and sea grass beds - the most important breeding grounds and nurseries for marine organisms, and home to the oceans' largest concentration of plant and animal species, are under particular threat. Reefs around the world, including Australia's Great Barrier Reef, are bleaching and dying as sea temperatures and acidity rise due to our increased atmospheric CO_2 emissions. Mangroves and salt-water marshes, drained and filled in, are being developed around the world, or are being converted to fish and shrimp farming operations. Removal of mangrove and marsh barriers expose more shoreline to the destructive effect of the oceans' storm surges,

The indiscriminate over-harvesting of ocean fish, especially by bottom trawling, the marine equivalent of forest clear-cutting, has depleted many of the world's fisheries. Many predatory marine fish populations in all regions of the Atlantic, Indian, and Pacific Oceans, are only 10% of what they were some 50 years ago. Many species of sea turtles, penguins, sharks, seals, fish like the Atlantic Bluefin Tuna (*Tunnus thynnus*), and whales like the North Atlantic Right Whale (*Eubalaena glacialis*), are endangered or critically endangered.

> *"The library of life is burning and we do not even know the titles of the books."*
>
> - Gro Harlem Brundtland,
> Former Director-General of the World Health Organization

Like other large whales, vast numbers of Humpback Whales have been slaughtered since industrial whaling operations that began as early as the 18th Century, driving Humpbacks to the edge of extinction. But spurred by an international public outcry, by major efforts of scientists like Roger Payne and others, and a host of conservation organizations, the International Whaling Commission banned commercial Humpback Whale hunting in 1966. Thanks to added protection under both the 1972 U.S. Marine Mammal Protection Act and the 1973 U.S. Endangered Species Act, Humpbacks have largely recovered over the past 50 years, though perhaps not to their original levels. Humpback populations have increased globally from 5,000 whales in 1966 to approximately 80,000 today.

While Humpbacks are not presently endangered, they are still being killed by human activity—entangled in fishing gear, struck by ships, and increasingly by ingesting plastic waste, which they cannot break down in their gastro-intestinal tracts, resulting in blockage and inflammation. In addition, underwater noise from ship motors and sonar can disrupt feeding and courtship behavior, and may play a role in the beaching of Humpbacks and other whales. With increased warming of the oceans, particularly of the Antarctic, krill populations are falling, threatening Humpbacks' main food source.

The recovery of Humpback Whale populations, one of the greatest of all conservation success stories, is testimony to what is possible when people are informed and active, of what can be accomplished when they care. The return of Humpbacks from the edge of extinction provides a model for other efforts to protect species that are threatened by human inaction and heedlessness, borne out of our inattention and our ignorance of what is in danger of being lost, borne out a fundamental misunderstanding about how we are ultimately and totally dependent for our health and for our lives on the living world.

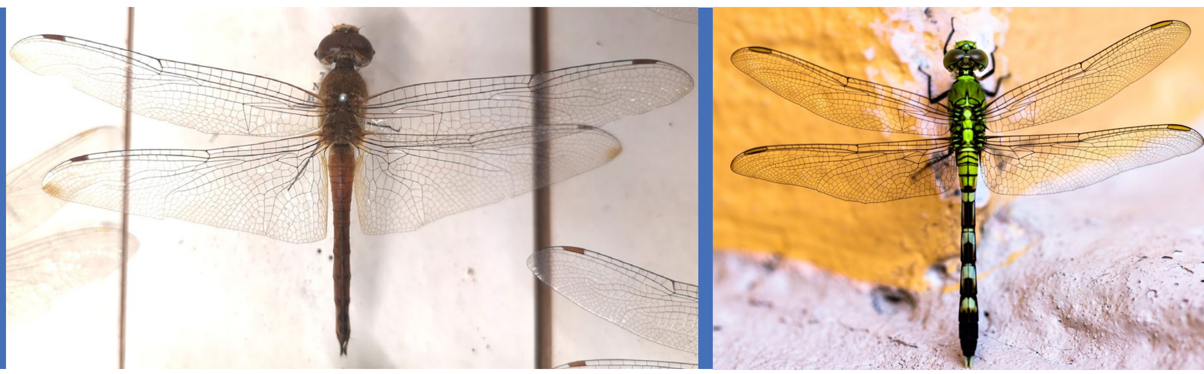
Afterword

We hope that the extraordinary organisms we have featured in this booklet, along with the sustainable engineering designs they have inspired, present a compelling case for why we must preserve biodiversity. Some still seem to believe we have a choice about whether we protect the plants, animals, and microbes we share our small planet with. The stark reality is that we have no choice, for it is these organisms that create the support systems that make all life on Earth, including human life, possible.

We also have no choice, because, with the current and ongoing mass extinction of species, we are losing sustainable engineering designs that Nature has "field tested" for us over many thousands and millions of years - designs that may be the most energy efficient and resource conserving, the most recyclable and least toxic to the living world, the most perfectly adapted to the tasks they perform. It is clear we must identify, understand, and apply these designs if humanity is to survive.

It is reasonable to ask whether the loss of a single species – especially one belonging to a large family of organisms – makes a difference. Wouldn't there be one or many others like it? If we look at dragonflies, for example, there are approximately 3000 known species, and all of them, appear to have the same basic wing structure and flight mechanics. If one of them were lost to extinction, wouldn't its fundamental aerodynamic design still exist? Such comparative research on dragonflies, however, has not been done, and it is therefore impossible to answer this question.

The Globe Skimmer Dragonfly (*Pantala flavescens*) (see Figure 31, left) is capable of the longest known non-stop flight of any insect (over 4400 miles). Its hind wings appear to be slightly broader at the base than those of other dragonflies (see Figure 31, right). While it has not yet been investigated, this slightly different design has led some experts to ask whether it may provide the Globe Skimmer with greater energy efficiency while flying or gliding compared to other dragonflies, enabling its remarkable flights. If it goes extinct, we might then lose a unique design before it has been studied, one that could lead to far more efficient micro-wind turbines, electrical generators capable of changing the lives of millions of people in developing countries.



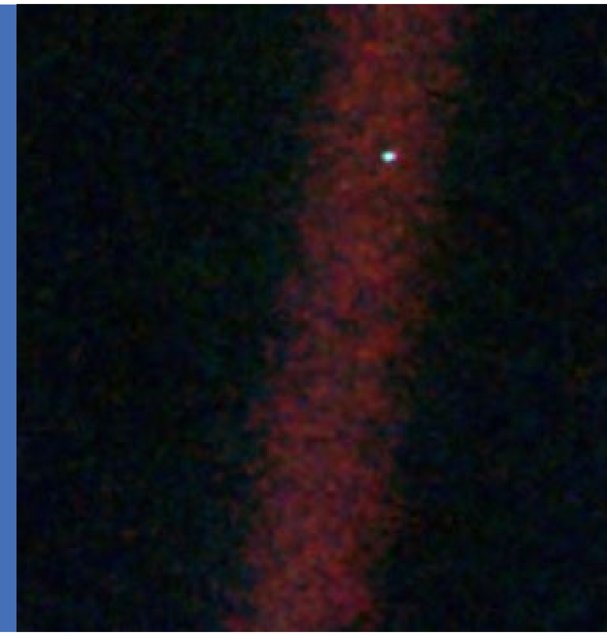
▲ **FIGURE 31 - UNIQUE DRAGONFLY WINGS**
On the left, a Globe Skimmer Dragonfly (*Pantala flavescens*). © The Trustees of the Natural History Museum, London. On the right, Eastern Pondhawk (*Erythemis simplicicollis*). © Jude Infantini on Unsplash

Or consider the Humpback Whale. While there are some 90 species of *Cetaceans*, which include whales, dolphins, and porpoises, the Humpback is the only species known to have tubercles on its flippers, a design that allows it to achieve extraordinary lift forces without stalling. We were incredibly lucky, given that these whales had been on the brink of extinction, to have noticed and studied this singular model for making some of the most energy efficient wind turbines and fans. If we had lost Humpbacks, we would have lost that model forever.

If losing even a single species can have enormous negative consequences for humanity, then what about the loss of millions, a future predicted by UN studies?

We simply must find a way to stop this self-destructive path we are taking.

We wish to close this booklet with the words of Carl Sagan, one of the world's leading astronomers and astrophysicists, who died tragically after a long illness just after he turned 62.



◀ **FIGURE 32 - THE PALE BLUE DOT**

Here is the photograph of the Earth, taken by Voyager I, as it appeared within a band of scattered sunlight. NASA/JPL-Caltech, Public domain

On February 14, 1990, when the Voyager I Spacecraft was some 4 billion miles from the Earth, a distance equivalent to more than 40 trips from the Earth to the Sun, Sagan suggested that NASA signal the Voyager's cameras to take pictures of the planets in our Solar System.

Sagan called the image that was taken of the Earth "a mote of dust suspended in a sunbeam," and referred to it as "the pale blue dot." Here is what he said about it.

"Look at that dot. That's here. That's home. That's us. On it everyone you love, everyone you know, everyone you ever heard of, every human being who ever was, lived out their lives....

Our planet is a lonely speck in the great enveloping cosmic dark. In our obscurity, in all this vastness, there is no hint that help will come from elsewhere to save us from ourselves.

The Earth is the only world known so far to harbor life. There is nowhere else, at least in the near future, to which our species could migrate. Visit, yes. Settle, not yet. Like it or not, for the moment the Earth is where we make our stand.

It has been said that astronomy is a humbling and character-building experience. There is perhaps no better demonstration of the folly of human conceits than this distant image of our tiny world. To me, it underscores our responsibility to deal more kindly with one another, and to preserve and cherish the pale blue dot, the only home we've ever known."

Suggested Readings, Videos, & Records

1. Paulson, Dennis. (2019) *Dragonflies and Damselflies: A Natural History*. Princeton, NJ: Princeton University Press.

2. McCoy, Dakota. (December 14, 2021) "Convergent optical illusions in colourful creatures." *Functional Ecologists.* https://functionalecologists.com/2021/12/14/convergent-optical-illusions-in-colourful-creatures/

3. Superhydrophobic/Superhydrophilic Videos

   Brigham Young University (May 21, 2014) *Engineers bounce water off superhydrophobic surfaces.* [Video] YouTube. https://www.youtube.com/watch?v=Sliv-hkRvZE

   National Science Foundation (July 24, 2014) *Ride of the Water Droplets.* [Video] YouTube. https://www.youtube.com/watch?v=UG4IMfH7I3E

   University of Rochester (January 20, 2015) *Using Lasers to Create Super-hydrophobic Surfaces* [Video] YouTube. https://www.youtube.com/watch?v=FLegmQ8_dHg

   Massachusetts Institute of Technology (December 21, 2012) *Jumping water droplets improve power-plant efficiency.* [Video] YouTube. https://www.youtube.com/watch?v=Qv1sUHnaGVI

4. Unwin, Mike & Tipling, David. (2017) *The Enigma of the Owl: An Illustrated Natural History,* New Haven, CT: Yale University Press.

5. Johnsgard, Paul R. (2002) *North American Owls: Biology and Natural History.* 2nd Ed., Washington, DC: Smithsonian Books.

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14. Payne, Roger. (1970) *Songs of the Humpback Whale* [Album] Capitol Records.

15. Giggs, Rebecca (2020) *Fathoms: The World in the Whale.* New York, NY: Simon & Schuster.

16. Ask Nature (https://asknature.org), an initiative of The Biomimicry Institute

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Biodiversity Conservation Programs
of the United Nations

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- Achim Steiner, Administrator, United Nations Development Programme (UNDP)

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- Anette "Peko" Hosoi, PhD - Professor of Mechanical Engineering and Associate Dean of Engineering, Massachusetts Institute of Technology

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