02.2023


NATIONAL
GEOGRAPHIC
THE FUTURE IS
FOLDED
HOW ORIGAMI IS RESHAPING OUR WORLD

1. The daytime sky's scattered blue light tints a just risen color-altered red moon (March 12, 2017).

2. Light passing through varied atmospheric densities is bent, changing how the moon's shape appears (February 15, 2014).

3. During a total lunar eclipse, when the moon is in Earth's shadow, bent red light falls on its surface (July 27, 2018).

MOON VIEWS IN RAINBOW HUES

THE MOON'S ACTUAL COLOR is an off-white brown-gray when its dusty surface is sunlit. But Earth's atmosphere modifies our views of the moon, altering colors and shape. Italian photographer Marcella Giulia Pace, who has captured lunar variations for 10 years, chose 48 of her images to compare in this spiral montage.

The varied colors appear when the moon is seen or photographed through stratified and irregular gas layers of Earth's atmospheric blanket. Tiny air molecules in the layers scatter light that hits them, and their structure causes blue light to scatter more readily than red or orange. When, for example, Pace photographs the moon through the densest air—as it rises and as it sits just above the horizon—this phenomenon is especially intense, glowing more red or orange. Other materials in the atmosphere—water droplets, dust, wildfire smoke—also influence the path of light and affect the moon's hue, and those colors are specific to the suspended materials themselves.

The moon's apparent shape also is altered as the light it emits travels through the stratified air. Because the atmosphere nearest Earth's surface is much denser than high above, the path of light traveling those varied densities will bend. The result: The light's source appears as a squished ellipse instead of a lunar disk. —LIZ KRUESI

PHOTO: MARCELLA GIULIA PACE (COMPOSITE OF 48 IMAGES)

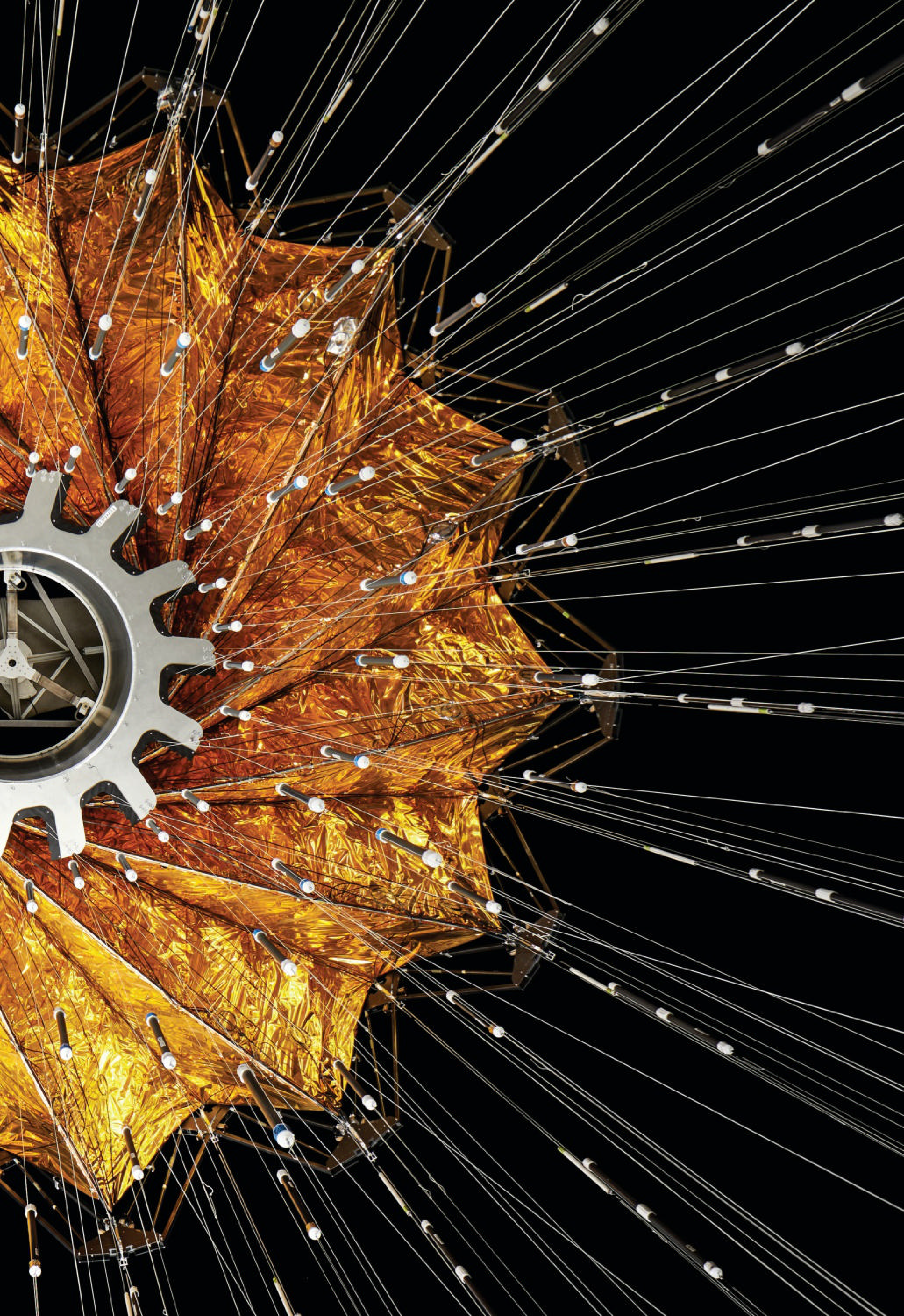
Origami artist and physicist Robert J. Lang folded this crane out of a single uncut square of paper. The complexity of this form—from spindly limbs to feathered wings—was once thought to be nearly impossible. But Lang, a pioneer in the use of mathematics in origami, designed the bird using geometric concepts at the core of a program called TreeMaker, which he developed in 1993 to test whether computers could help design origami.

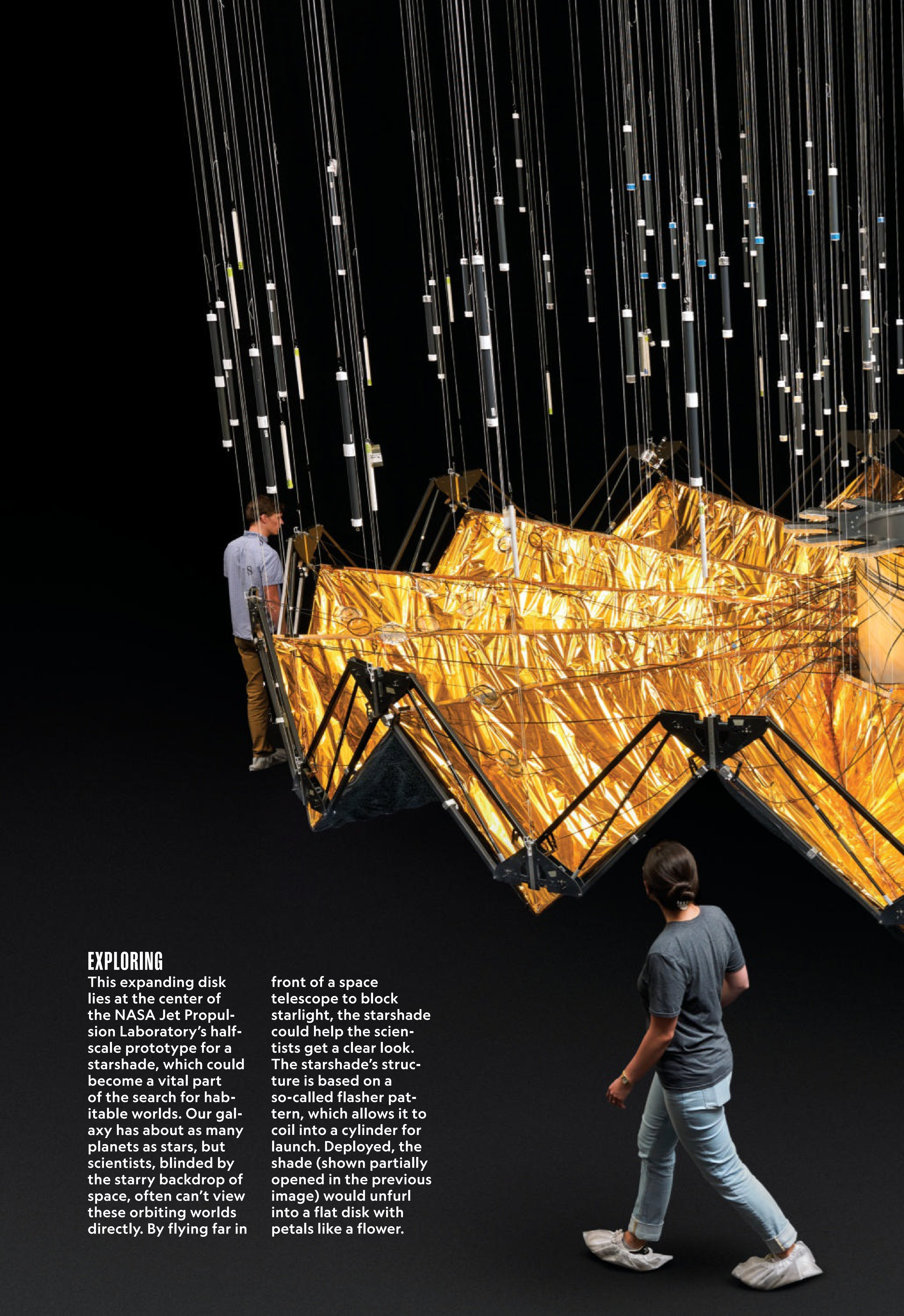
THE FUTURE IS FOLDED

ORIGAMI HAS LONG INSPIRED ARTISTS. NOW IT'S BLAZING NEW TRAILS IN SCIENCE AND TECHNOLOGY.

BY **MAYA WEI-HAAS**

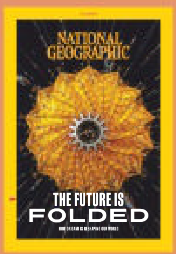
PHOTOGRAPHS BY **CRAIG CUTLER**





EXPLORING

This expanding disk lies at the center of the NASA Jet Propulsion Laboratory's half-scale prototype for a starshade, which could become a vital part of the search for habitable worlds. Our galaxy has about as many planets as stars, but scientists, blinded by the starry backdrop of space, often can't view these orbiting worlds directly. By flying far in front of a space telescope to block starlight, the starshade could help the scientists get a clear look. The starshade's structure is based on a so-called flasher pattern, which allows it to coil into a cylinder for launch. Deployed, the shade (shown partially opened in the previous image) would unfurl into a flat disk with petals like a flower.



Make your own starshade

This month's cover features a starshade prototype that NASA is testing for deployment in space. Origami makes packing the shade on a rocket possible. The exercise on the next page allows you to test the basic principles of the design yourself.

UNFOLDING THE SCIENCE

ORIGAMI, EVERYWHERE

Engineers are increasingly turning to the centuries-old art of folding paper into three-dimensional forms to shape some of the modern world's most ambitious designs. The models shown here, many of which are still prototypes, demonstrate the exciting potential of future technologies. Not only are designs less expensive and faster to manufacture in two-dimensional form, but folding also opens a new realm of scale, materials, and mechanical movement, with applications ranging from repairing our bodies to exploring outer space.

ALBERTO LUCAS LÓPEZ, NGM STAFF; LAWSON PARKER
ART: MATTHEW TWOMBLY
SOURCES: ITAI COHEN, CORNELL UNIVERSITY; NASA EXOPLANET EXPLORATION PROGRAM; EDUCATIONAL MUSEUM OF ORIGAMI IN ZARAGOZA (EMOZ); MARCO MELONI AND OTHERS, *ADVANCED SCIENCE*, JULY 2021

SECTORS USING ORIGAMI

ORIGAMI-BASED DESIGN

UNDERLYING ORIGAMI STRUCTURE

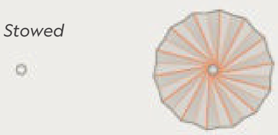
HOW IT WORKS

SPACE EXPLORATION

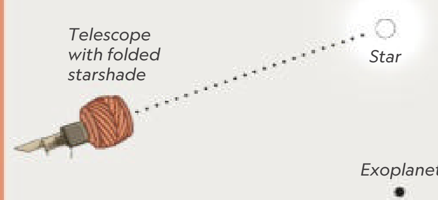
Space missions need structures that are lightweight and versatile, compact during transport, and large once deployed. Origami-inspired space tools have grown to include antennas, photovoltaic arrays, sun shields, and solar sails.

Starshade exoplanet exploration

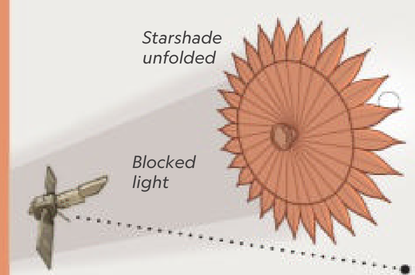
A starshade would fly between a telescope and a distant star, blocking the star's light so that orbiting exoplanets could be seen and studied for signs of life. The starshade, folded to fit within a 16-foot-wide launch vehicle, would grow to about the size of half a football field once fully extended.



The inner disk when deployed is much like a bicycle wheel: An outer truss is supported by spokes tensioned against a center hub. A motor unfurls a folded optical shield 65 feet in diameter.



Flying in tandem with a space telescope, the starshade would use thrusters to position itself 31,000 miles in front of it, covering a star that can blaze 10 billion times as bright as its exoplanets.



BIOMEDICAL ENGINEERING

One of the fields most advanced in de
ing origami-based designs, the biome
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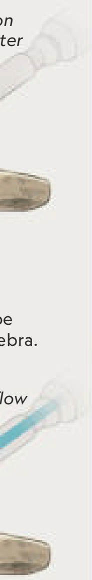

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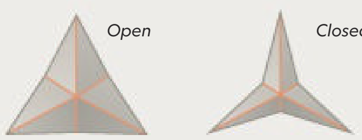
STRUCTURAL ARCHITECTURE

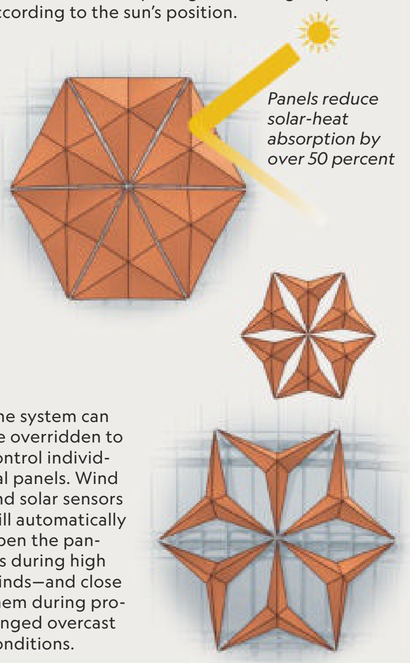
Originally adopted by architects for aesthetic reasons, origami-based designs can also reduce energy demands and improve structural performance. Some are responsive to their environment, changing shape in reaction to light or acoustics.

Al Bahar Towers' responsive facades

Battling an environment of intense heat and blowing sand, two towers in the United Arab Emirates built in 2012 are each composed of 1,049 origami-like shading elements. The screens are responsive to sun exposure, opening in broad daylight to provide shade and conserve energy.



Each shading device is made of fiberglass mesh and weighs about 1.7 tons. Sun-tracking software controls the opening and closing sequence according to the sun's position.



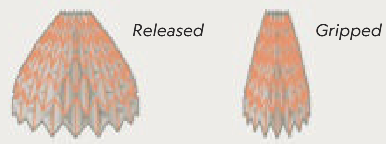
The system can be overridden to control individual panels. Wind and solar sensors will automatically open the panels during high winds—and close them during prolonged overcast conditions.

ROBOTICS

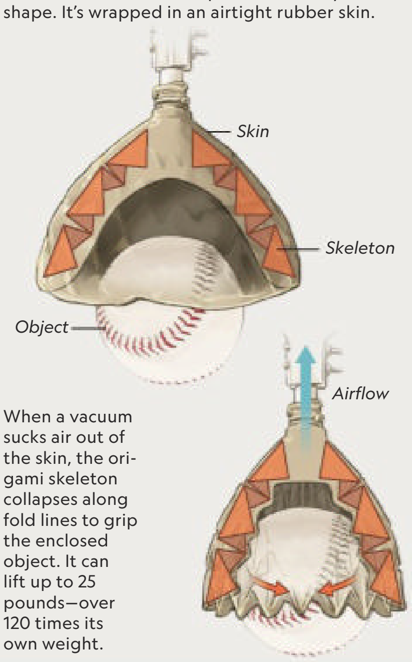
Compared with conventional robotics, origami designs, when manufactured in two dimensions and then assembled into three, can be both easier to store and more cost-efficient—all while supporting complex computational and sensing mechanisms.

Vacuum-driven gripper

Rigid robotic hands lack dexterity, but soft bots often lack strength. An origami skeleton allows this gripper to mold around fragile items without compromising brawn, lifting anything from a single broccoli floret to a hammer. It could someday work on a factory assembly line—or around the house.



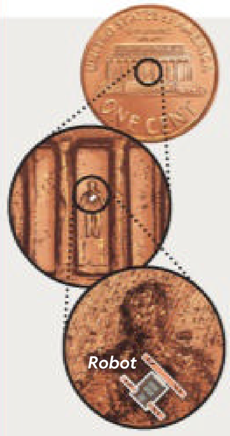
The bell-shaped gripper has a foldable, silicone rubber skeleton based on an origami pattern that can shift between a spherical and a cylindrical shape. It's wrapped in an airtight rubber skin.



When a vacuum sucks air out of the skin, the origami skeleton collapses along fold lines to grip the enclosed object. It can lift up to 25 pounds—over 120 times its own weight.

MICROSCOPIC ENGINEERING

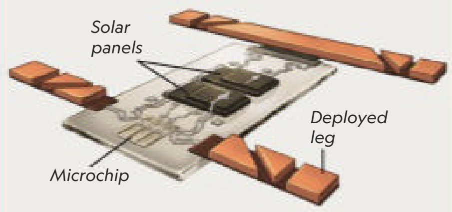
Imagine a robot so small that thousands can be injected through the tip of a needle—aiding microsurgery, cleaning bacteria from surfaces, or exploring worlds at a new scale. Invisible to the naked eye, some can fold appendages, becoming 3D forms that then walk or swim.



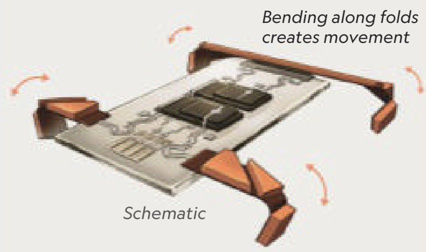
Mass-manufactured microscopic robots

More than one million robots—each less than 100 micrometers long—can be manufactured onto eight-inch disks. These microscopic robots (see penny size comparison) have detectors, power sources, and circuits that will enable them to sense, interact with, and control their local environment.

Robotic limbs are built around a flat microchip that acts as a brain. Powered by light, electrochemical reactions create stress and bend the base layer of the legs.



Sections of rigid material restrict bending to predetermined origami-like folds to achieve the desired 3D position. The microchip brain coordinates limb movements to form an autonomous walking robot.



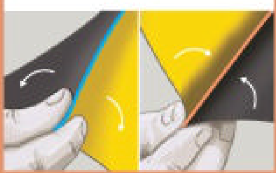
MAKE YOUR OWN

ORIGAMI STARSHADE

Use this classic origami method to craft a model of the optical shield that may someday help NASA capture images of planets outside our solar system. Scan this QR code or visit *natgeo.com/starshade* to access and print out a larger template for easier folding.

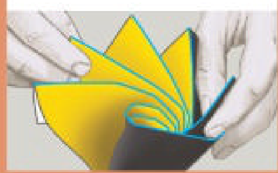
1 Cut and crease

Cut along dotted lines and crease along fold lines. Blue lines are "mountain folds" that rise up. Orange lines are "valley folds" that point down. Gently run a pencil or fingernail along fold lines to help with creasing.



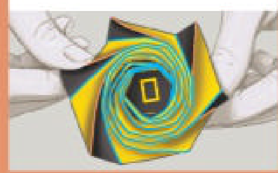
2 Fold and gather

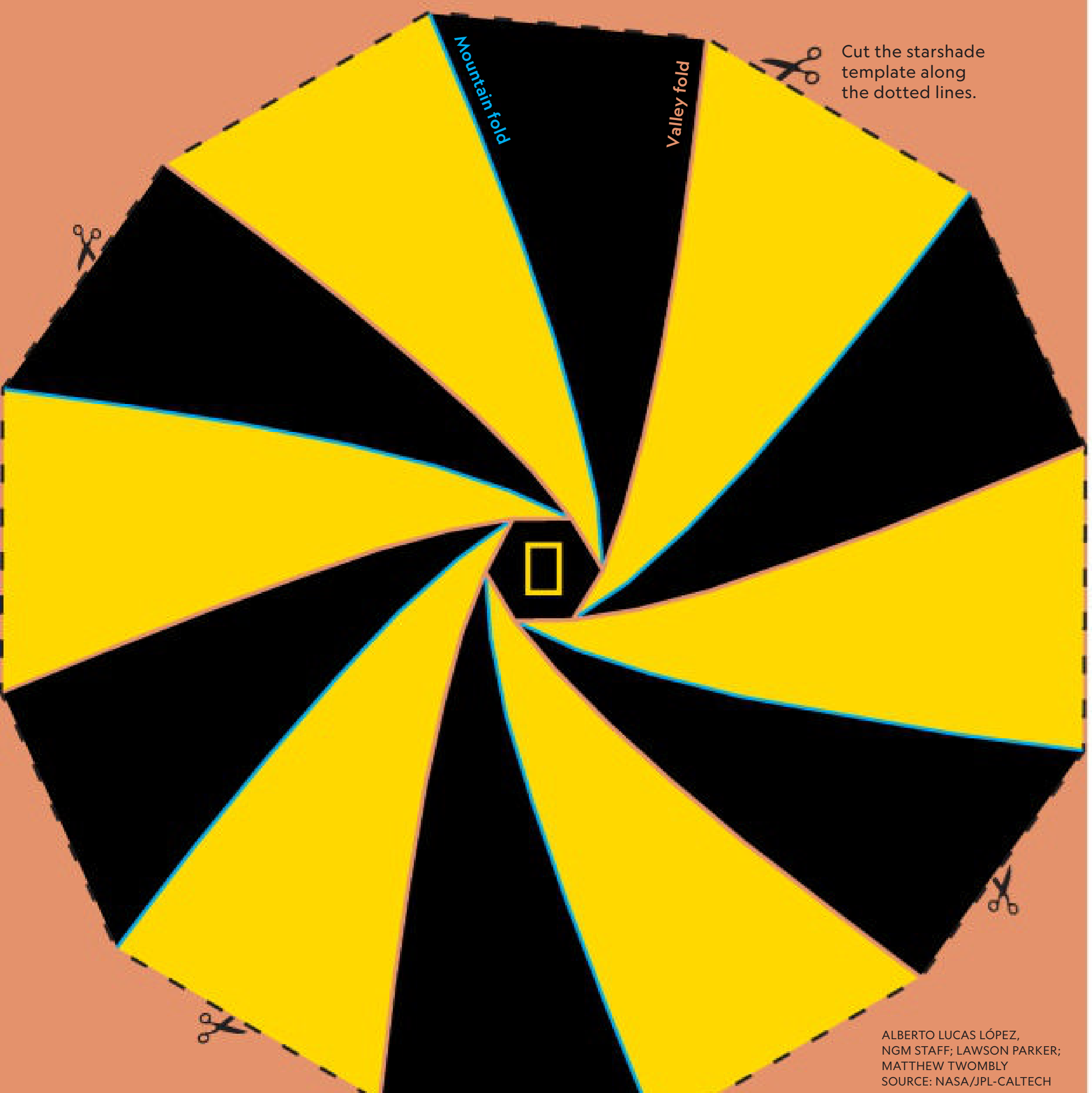
Once all lines are creased, fold along all fold lines, moving from the center outward. Lines will fold 180 degrees. Hold the central, base hexagon flat while rotating and gathering the folds into a spiral shape.



3 Furl and unfurl

This folded model represents a starshade's inner-disk optical shield when it's stowed before launch. Open and close the starshade by pulling opposite edges of the sheets apart, then pushing them back together.





ALBERTO LUCAS LÓPEZ, NGM STAFF; LAWSON PARKER; MATTHEW TWOMBLY
SOURCE: NASA/JPL-CALTECH

festoon sake bottles at Shinto weddings. As paper prices fell, origami's uses spread to gift wrap, playthings, and even geometry lessons for kids.

Then, in the mid-20th century, origami master Akira Yoshizawa helped elevate paper folding to a fine art. He breathed life and personality into each creature he designed, from a stern-faced gorilla glowering out of sunken eyes to a baby elephant joyfully swinging its trunk. With the publication of his first origami book in 1954, Yoshizawa also made the art form more accessible, establishing an easily understandable language of dotted lines, dashes, and arrows that contributed to systems still used today.

In the late 1950s, Yoshizawa's delicate forms inspired Tomoko Fuse, now one of the foremost origami artists in Japan. Her father gave her Yoshizawa's second origami book when she was recovering from diphtheria as a child. Fuse methodically crafted every model, and she's been entranced with origami ever since. "It's like magic," she says. "Just one flat paper becomes something wonderful."

Among her many achievements, Fuse is famous for her advances in modular origami, which uses interlocking units to create models with greater flexibility and potential complexity. But she thinks of her work as less about creation than about discovering something that's already there, "like a treasure hunter," she says. She describes her process as if she's watching from afar, following wherever the paper leads her. "Suddenly, beautiful patterns come out."

Indeed, origami taps into patterns that echo throughout the universe, seen in natural forms such as leaves emerging from a bud or insects tucking their wings. For these exquisite folds to become scientifically useful, however, researchers must not only discover the patterns but also understand how they work. And that requires math.

PUTTING NUMBERS to origami's intriguing patterns has long driven the work of Thomas Hull, a mathematician at Western New England University in Springfield, Massachusetts. When I walk into his school's math department, I know immediately which office is his. The door at the end of the hall is ajar, revealing boldly colored paper folded in all manner of geometric shapes. The models fill every nook of

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