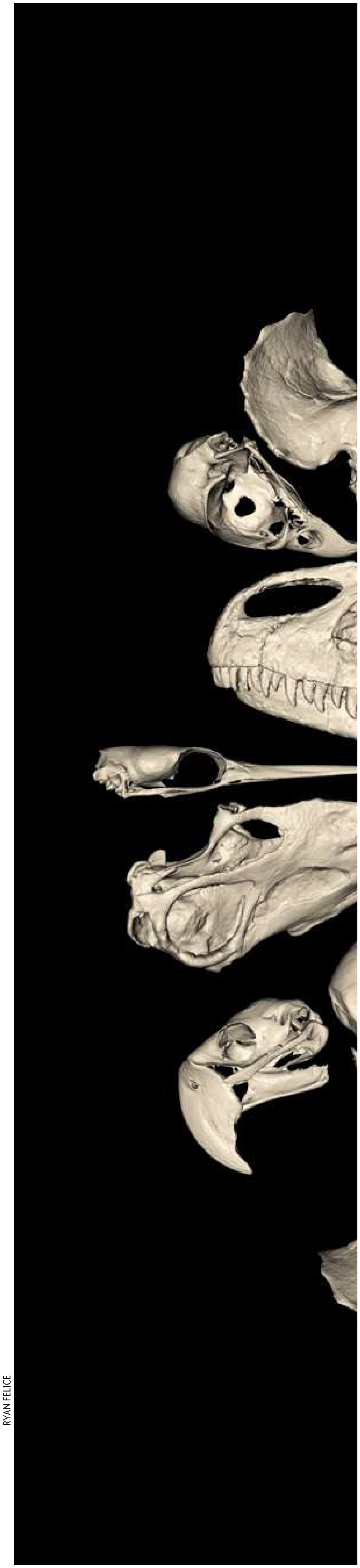
How Birds Branched Out

Modern birds are incredibly diverse. A new study reveals how they achieved their spectacular evolutionary success

By Kate Wong



RYAN FELICE

ARRAY of bird and nonbird dinosaur skulls.

THIS PAST MAY, WHEN IT FINALLY SANK IN THAT I WAS GOING TO BE STUCK AT HOME FOR A VERY long time because of the pandemic, I took up a hobby that had never especially appealed to me before: birding. I cleaned my neglected bird feeder and filled it with seed, retrieved my binoculars from a gear bag in the basement, and started having my morning coffee outside, slowly learning to identify species based on body size, feather colors, beak shape and song. At last count I had logged 39 species from the confines of my suburban backyard. These hours spent observing birds—the goldfinches congregating at the feeder, the pileated woodpeckers drumming in the trees, the turkeys strutting across the lawn, the ruby-throated hummingbirds hovering above their favorite blooms, the red-shouldered hawks circling overhead—have given me a newfound appreciation for their diversity. And I am seeing only a sliver of the actual richness of avian forms. With more than 10,000 species alive today, birds constitute the most diverse group of land vertebrates (backboned animals) on Earth. How did they come to be so spectacularly varied?

Birds are dinosaurs, the only lineage to survive to the present day. They arose in the Jurassic period, between 200 million and 150 million years ago, from the theropods, a group of two-legged carnivorous dinosaurs whose members include both the behemoth *Tyrannosaurus rex* and the daintier *Velociraptor*. For tens of millions of years birds evolved alongside other dinosaurs, diversifying into a number of small-bodied, fast-growing, feathered fliers, along with a few large-bodied, flightless forms. One group, the so-called neornithines, or new birds—distinguished by their fused foot and anklebones and by certain traits in the bones that support the wings—would eventually give rise to modern avian-kind.

Scientists have tended to view modern bird diversity as the result of a burst of evolutionary activity that occurred after the fateful day 66 million years ago when a six-mile-wide asteroid struck Earth, dooming 75 percent of plant and animal species, including the nonbird dinosaurs and most bird groups. Exactly why the neornithine lineage alone survived this apocalypse is uncertain, although the recent discovery of a 66.7-million-year-old neornithine bird fossil from Belgium called *Asteriornis,* a relative of today's ducks and chickens, suggests that being small and living in a shoreline environment may have helped. In any case, the idea was that after the mass extinction, the neornithine birds had the place largely to themselves. Free of competition from other dinosaurs (not to mention a whole bunch of other vertebrates that also perished, including the pterosaurs, those flying reptiles that had long ruled the skies), birds abruptly exploded into a multitude of forms to fill the many newly vacant ecological niches.

Now a new analysis has turned up intriguing evidence that their extraordinary diversity might not have originated that way. In a study of hundreds of bird and dinosaur skulls, Ryan Felice of University College London, Anjali Goswami of the Natural History Museum in London and their colleagues found that in the aftermath of the mass-extinction event, the pace of birds' evolution actually slowed way down compared with that of their dinosaur predecessors, rather than accelerating as expected. The paper, published in *PLOS Biology,* reveals the rate of evolution during the radiation of a major vertebrate group and hints at factors that may have played a key role in determining its course.

Fossils that preserve the entire skeleton of an animal are extremely rare, so comparative studies of fossil material tend to focus on a particular region of the body. The team looked at skulls because they serve many functions, from supporting sense organs to enabling feeding to attracting mates to defending themselves. "Birds have incredible diversity in the shape of their skulls," Felice observes. Consider hawks versus hummingbirds, he says, or pigeons versus pelicans. "Did birds evolve their highly variable skulls by evolving more rapidly than their nonavian dinosaur ancestors?" Felice asks. That might seem like a narrow question, but "it gets toward an understanding of how diversity evolves," he explains. "If a group of organisms is really diverse, do they achieve their diversity quickly in an explosive burst? Or is it slow and steady?"

To investigate, the team carried out a detailed shape analysis of 391 well-preserved skulls from modern birds

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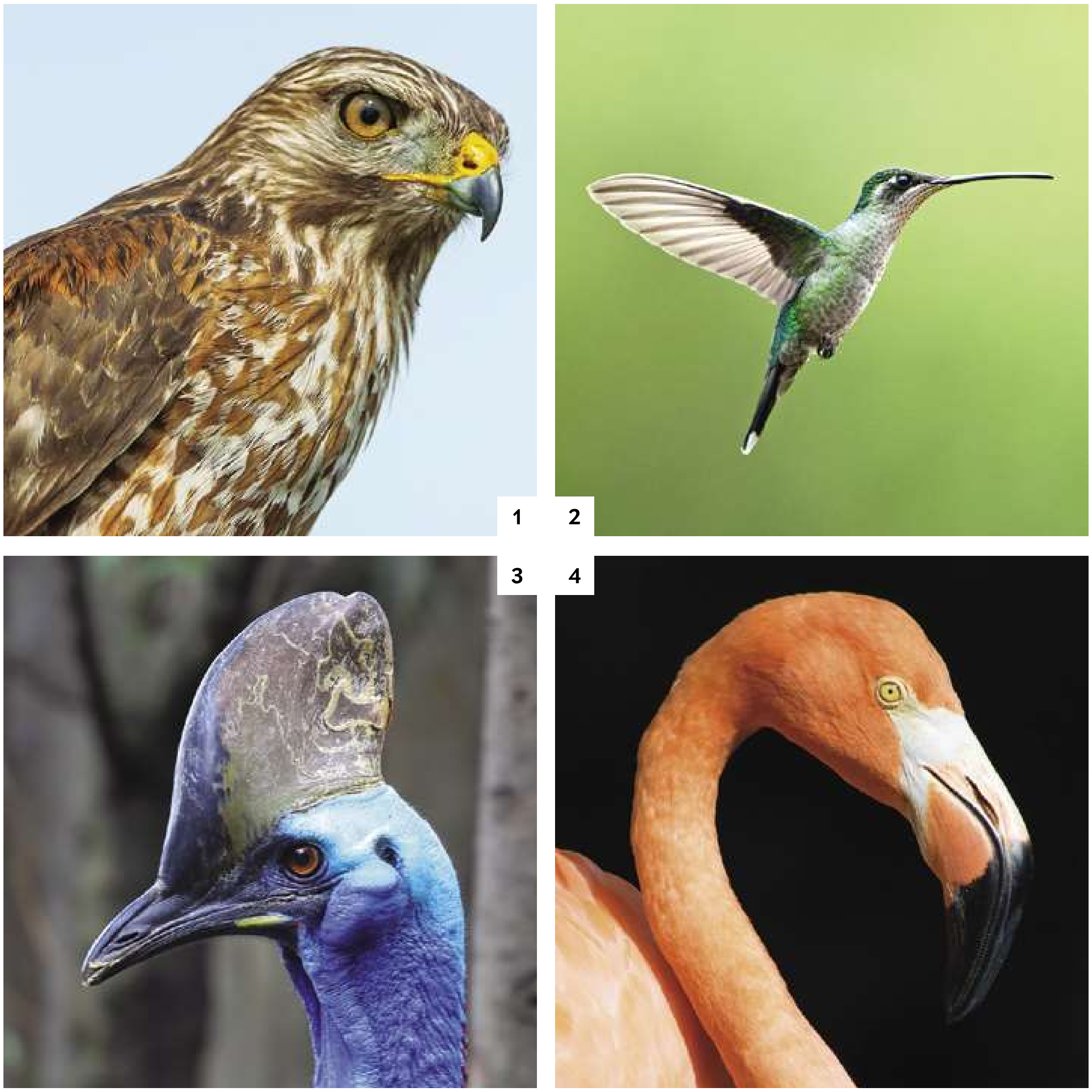


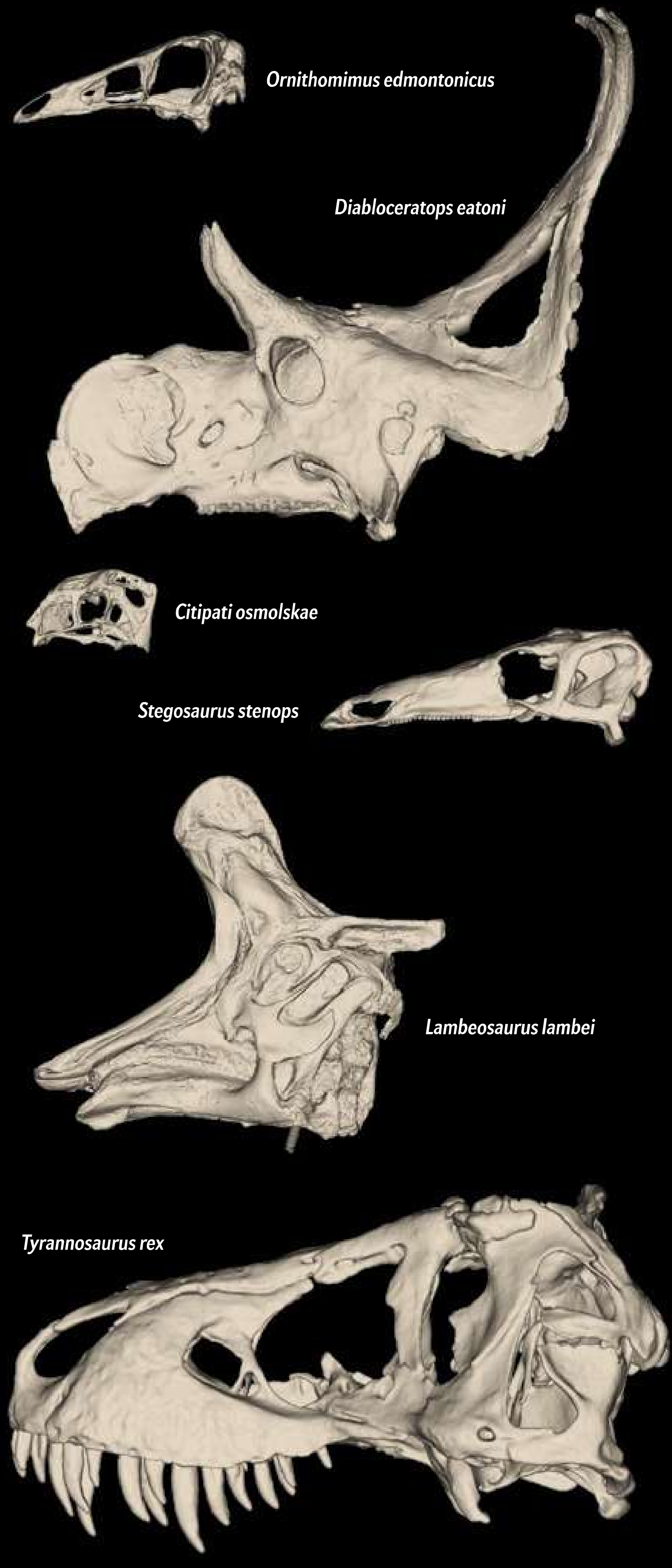
MODERN BIRDS exhibit a myriad of forms, with more than 10,000 species alive today. They are found on every major landmass and body of water on Earth and have evolved to exploit a wide variety of ecological niches. Shown here are a red-shouldered hawk (*1*), a magnificent hummingbird (*2*), a cassowary (*3*) and a flamingo (*4*).

ENRIQUE AGUIRRE AVES *Getty Images* (*1, 2*); JORDAN CAPITAN *Getty Images* (*3*); TASHINA VAN ZWAM *Getty Images* (*4*)

and extinct dinosaurs using high-resolution 3-D scans of the specimens. The scientists used the results to reconstruct the animals' evolution. Typically skull-shape comparisons rest on the use of established landmarks—such as sutures and bumps—that all the various species under evaluation share. But the larger the study group, the fewer the points of correspondence. As a result, investigations that focus on traditional landmarks lose much of the information about skull shape. "Our approach takes those landmarks and uses them as anchors for curves that connect up those landmarks and, in doing so, outline and delimit the individual bones of the skull," Goswami says. "Our automated approach then takes a generic template of points and fits the exact same template to all the specimens in our data set by using the landmarks and curves to identify the regions of interest. So you can get points distributed across the surface of a bone in a consistent way, regardless of whether the bones you are looking at look like the flat, bony structure under the beak of a duck or the tall, biting [snout] of a *T. rex*."

What the researchers found was that dinosaurs evolved 1.5 to three times faster than birds in all regions of the skull. After the mass-extinction event brought the Mesozoic era to a close and ushered in the Cenozoic era, birds branched into most of the major modern groups, from hummingbirds and penguins to birds of prey and songbirds. But they evolved this diversity far more slowly than their Mesozoic dinosaur forerunners. "Their rate of morphological change declines just as they are taking off as a radiation," Goswami says.

Why the sudden deceleration? Goswami thinks it reflects a shift in priorities for skull function. Whereas dinosaur skulls have elaborate display and fighting



SKULLS of nonbird dinosaurs are more diverse than those of birds.

RYAN FELICE

structures, as well as complex feeding mechanisms that require large areas for jaw-muscle attachment, bird skulls are mostly dedicated to housing and protecting the animals' comparatively large brain, she explains.

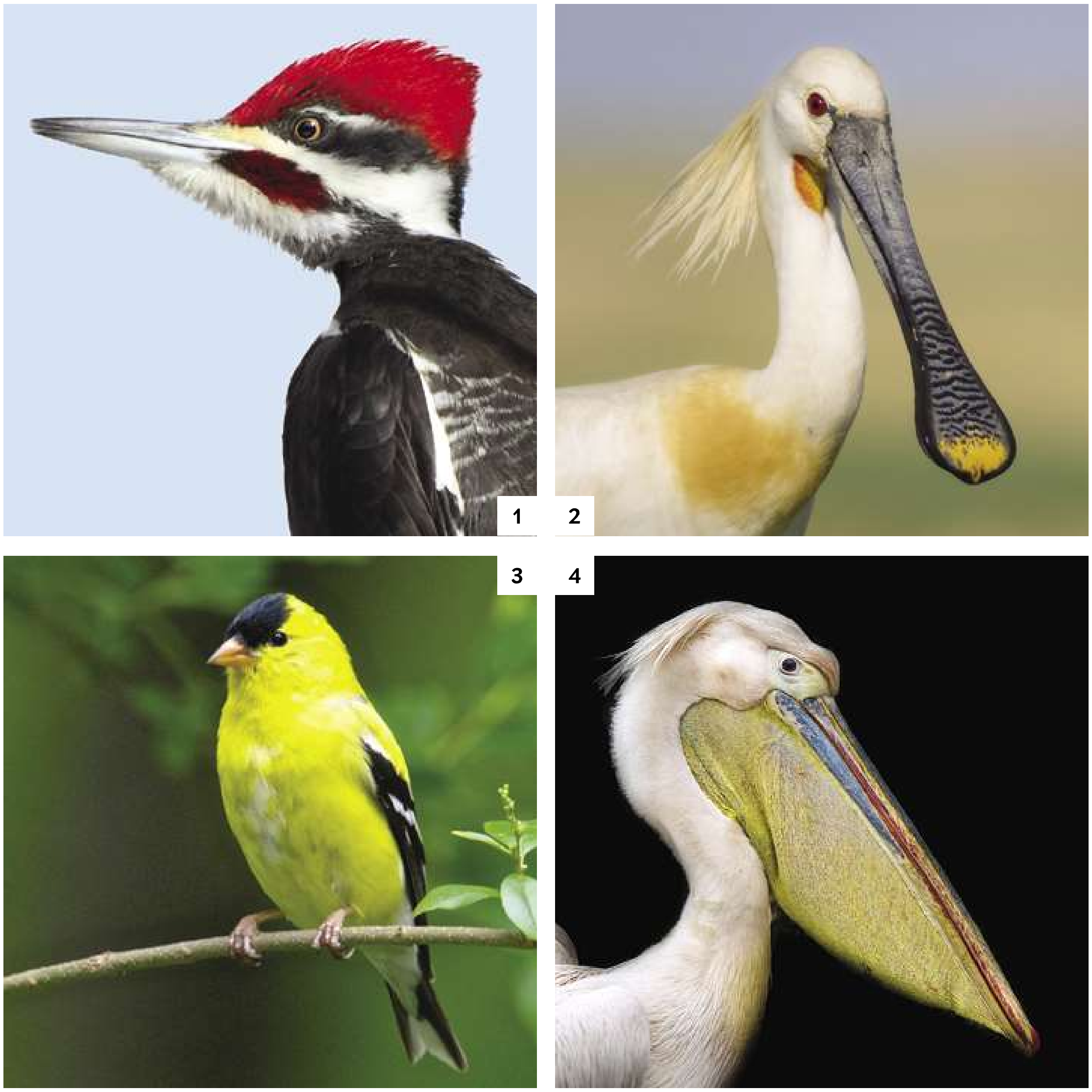
Bird-evolution experts who were not involved in the new research praised the team's methodology and the vast number of species they included in their study.

The finding that dinosaurs had a much faster rate of skull evolution than modern birds might seem strange considering the variety of bills in birds such as spoonbills, flamingos and pelicans, says Daniel Ksepka of the Bruce Museum in Greenwich, Conn. Their sundry shapes suggest a high rate of evolution in the beak, which is a major component of the skull. But a closer look reveals that these distinctive bills are the exception rather than the rule, he says. "There are plenty of groups where dozens of related species share a pretty similar skull shape, like warblers or parrots, suggesting relatively little skull evolution," Ksepka observes.

In contrast, some groups of dinosaurs clearly had sky-high rates of skull evolution. Among the ceratopsians (*Triceratops* and its kin), for instance, "each species had a unique arrangement of horns and crests. And these seem to have evolved rapidly because of their value for attracting mates," Ksepka says. "So many dinosaurs had these elaborate skull ornaments, but they are very rare in birds—the cassowary is one awesome exception," he adds. The large, flightless cassowary, a relative of the emu found in the tropical forests of Papua New Guinea and northeastern Australia, has a prominent bony crest atop its head. "It's likely that feathers took over the display role, as we have plenty of modern birds with plain-shaped skulls but beautiful feathered head crests. Just look at your friendly backyard cardinals and blue jays."

The discovery that bird skulls resulted from relatively low evolutionary rates "is essentially opposite from what we know of the rest of the skeleton," says Stephen Brusatte of the University of Edinburgh, another outside expert. Previous studies by Brusatte and others have focused on parts of the body other than the skull and found that these regions evolved faster in birds than in other dinosaurs. "What this means, I think, is that the origin of birds was driven by rapid and remarkable changes to the skeleton, particularly turning the arms into wings for flight. The heads were less important in this transition, and they probably lagged behind the rest of the skeleton." Early on in their evolution, birds seem to have hit on a head design that worked for them, with such features as a beak, big eyes and a large brain, he says: "Birds didn't need to radically change any of these things in order to adapt to different niches." Instead, Brusatte suggests, "after birds split off from other dinosaurs and went into the skies, they adapted to new niches by changing their body sizes, wing shapes and flying styles more than their heads."

Such mosaic evolution, in which different parts of the body evolve at different rates, is known to have



DIVERSITY of modern birds—from the pileated woodpecker (*1*) to the Eurasian spoonbill (*2*) to the American goldfinch (*3*) to the great pelican (*4*)—has been seen as the product of a burst of evolutionary activity that took place in the aftermath of the end-Cretaceous mass extinction. New research, however, suggests birds evolved their astonishing variety slowly.

occurred in many organisms, including humans. Ksepka notes that the ceratopsians' high rate of skull evolution contrasts starkly with barely discernible changes in their limb bones. Meanwhile modern warblers, he says, exhibit very little change in skull shape but have evolved "a kaleidoscope of color patterns."

But Goswami has a hunch that other parts of the bird skeleton may have also evolved on a relatively leisurely timetable. Nonbird dinosaurs transitioned between bipedal and quadrupedal body plans several times over the course of their evolution and did a lot of different things with their forelimbs, she points out—think of *T. rex*'s puny arms compared with a titanosaur's tree trunks. In contrast, once birds became specialized for flight as their forelimbs morphed into wings, among other changes, they never really evolved completely new body plans—presumably because of the developmental or functional constraints of being a bird. "I expect that future studies with sampling as broad as ours will also start to find that birds are, quite frankly, not keeping up with the pace of evolution observed in the other dinosaurs," Goswami says.

Of course, the birds are no less spectacular for that downturn. They survived fire and brimstone, conquered the skies and diversified into the dazzling array of feathered wonders that share the planet with us today. Slow and steady won the race. ■

BRIAN LASENBY *Getty Images* (1); *Getty Images* (2); GARY CARTER *Getty Images* (3); TASHINA VAN ZWAM *Getty Images* (4)

FROM OUR ARCHIVES

The Origin of Birds and Their Flight. Kevin Padian and Luis M. Chiappe; February 1998.
Taking Wing. Stephen Brusatte; January 2017.
Winged Victory. Kate Wong; November 2019.

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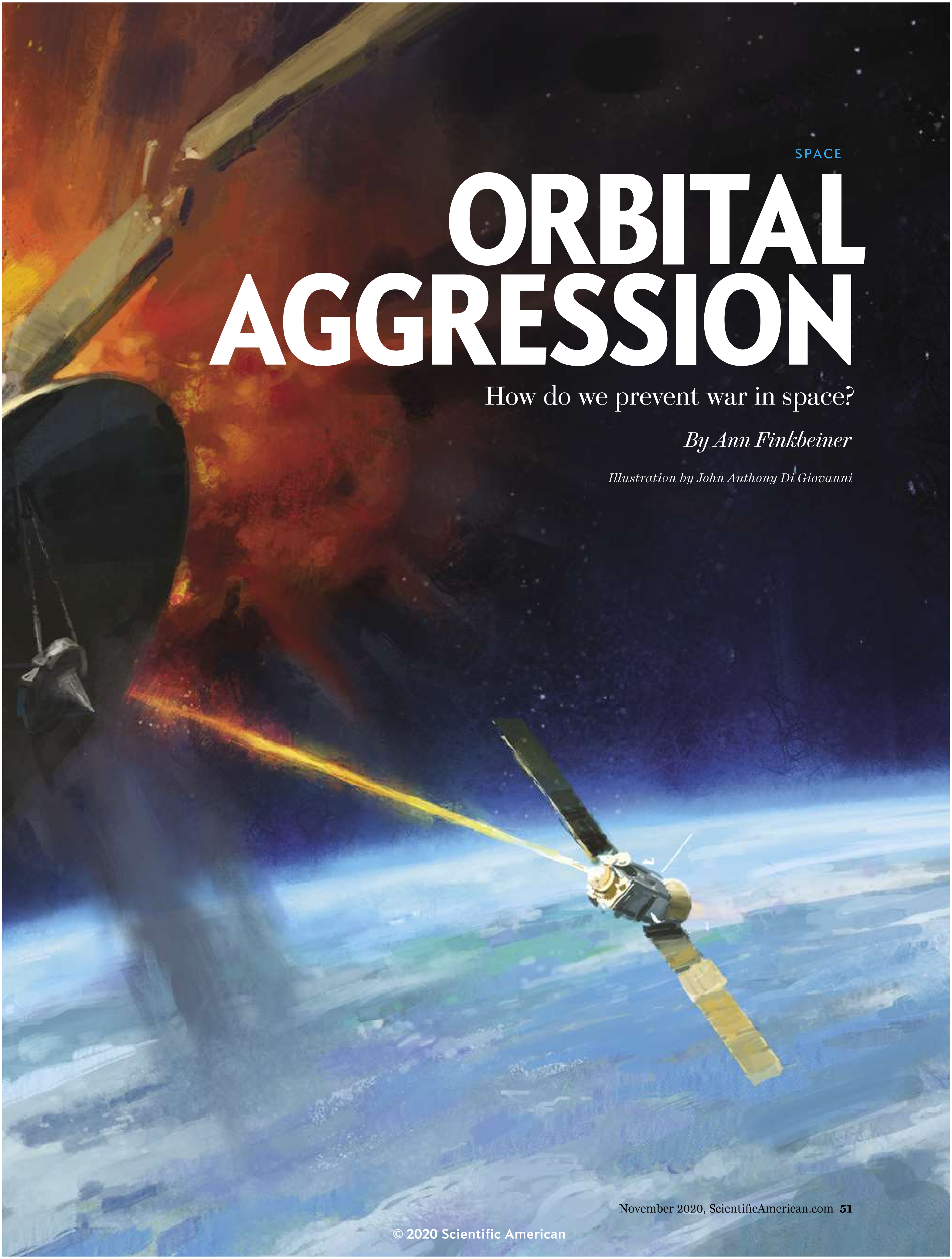

SPACE

ORBITAL AGGRESSION

How do we prevent war in space?

By Ann Finkbeiner

Illustration by John Anthony Di Giovanni

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ON JANUARY 30, 2020, AN AMATEUR SATELLITE WATCHER TWEETED, "Something to potentially watch." Cosmos 2542, a Russian inspection satellite, was "loitering around" USA 245, an American spy satellite, and, he wrote, "as I'm typing this, that offset distance shifts between 150 and 300 kilometers." USA 245 then adjusted its orbit to get away from Cosmos 2542, which in turn tweaked its own orbit to get closer again. "This is all circumstantial evidence," the watcher wrote, but "a hell of a lot of circumstances make it look like a known Russian inspection satellite is currently inspecting a known U.S. spy satellite."

Laura Grego, an astrophysicist who studies space technology, saw the tweets; she catalogues satellites, so she has been reading amateur watchers' communications, she says, "since before Twitter was invented." One country's satellite stalking another's is exactly what people like Grego, who worry about space war, worry about. Space war is not warfighters shooting one another in space. Nor is it war from the highest of all military high grounds: "Satellites don't 'drop' bombs," Grego says, "and aren't faster, better or less expensive than other ways of bombing." Space war is war on satellites. Cosmos 2542 could have been equipped to interfere with or damage USA 245 or to blow it to pieces. And if it had done so, the U.S. might have retaliated, perhaps by destroying a Russian spacecraft, and we might have had a space war. And then which satellites, and which services civilization depends on, would be destroyed?

For the U.S. more than anyone else, space war could be ruinous. The country relies heavily on its satellites to transmit signals for GPS, credit-card transactions, hospital systems, television stations, weather reports; the list goes on and on. But it depends more than any other country on its military satellites for communication and surveillance. And all satellites—bright and moving in predictable, public orbits—are essentially sitting ducks, nearly impossible to defend; space war is what the military calls "offense-dominant."

The U.S. military's solution to vulnerability is, of course, military. Last December the Department of Defense created the Space Force, saying that Russia and China had "weaponized space" and that space is now a "warfighting domain." Space Force's job is to protect U.S. satellites and to respond to bad behavior by adversaries.

Cosmos 2542, as the then head of Space Force, General John Raymond, sternly told *Time* magazine, "has the potential to create a dangerous situation in space." But Cosmos 2542's stalking turned out not to start a space war. Neither Grego nor the amateur watchers know what Cosmos was doing, but their best guess is that it was something like what Russian trawlers do when they hang around U.S. Navy ships: annoy, or intimidate if possible, and see what they can see. In any case, in mid-March the amateur watcher tweeted that USA 245 had made a small maneuver "that will put it at a distance of thousands of kilometers for weeks to come if not months," and after that Cosmos 2542 took itself elsewhere. Before it did, Grego added her own tweet: "A good time to establish some shared understandings about how close is too close."

Grego is at the Union of Concerned Scientists, a nonprofit that is part of the three worlds—nongovernmental organization (NGO), military and diplomatic—focused on space war. To her, the best way to stop a space war is to enter an international agreement to prevent or limit one. So far negotiations are stalled in international politics. Diplomats never work fast, Grego says, but right now they are "splashing around in the puddle of diplomacy" without getting much done.

So here we are, with the possibility of an escalating space war that would bring certain and incalculable civilian consequences. Yet attempts at diplomacy have been lackluster, and the military's response sounds as aggressive as it does protective. "I don't know if space war is imminent," says John Lauder, a 30-year veteran of the intelligence community's arms-control monitoring efforts, "but there are trends that make space more dangerous. It's not sitting on top of us, but it's moving in our direction at a rapid speed."

SPACE PEARL HARBOR

FOR ALMOST AS LONG as there have been satellites, there have been weapons to use against them and networks to track them. Satellite number one, of course, was Sputnik 1, put into orbit by the former U.S.S.R. on October 4, 1957. Sputnik and its successors were tracked immediately by amateurs with cameras; by February 1959 the Defense Advanced Research Projects Agency had set up the first satellite-surveillance network. The first antisatellite weapon was a missile called High Virgo, launched by the U.S. on September 22, 1959. In 1963 the former U.S.S.R. tested the first "satellite fighter"; in a 1968 test, another satellite fighter entered the same orbit as a U.S.S.R. target satellite, maneuvered next to it and exploded.

After this energized beginning, the U.S. and the former Soviet Union turned their attention from space war to the nuclear balances of the cold war. The U.S. spent the subsequent decades building satellites that were "exquisitely capable and costing billions of dollars and functioning very, very well," says Brian Weeden of the Secure World Foundation. "But they were not built with the idea of having an adversary do something to them." Once the U.S.S.R. collapsed, he says, "America thought it would be dominant in space forever."

Space war appeared briefly on the U.S. agenda in 2001, when a security commission report, headed by Donald Rumsfeld before he left to become secretary of defense, warned of U.S. vulnerability and included the notable phrase "a Space Pearl Harbor." Douglas Loverro, then an air force program director, began advocating for a kind of space force, but "9/11 happened, and everybody forgot about space," he says.

Meanwhile, Grego says, France, Japan, the U.K. and India had launched their own satellites, and more nations had built, bought or operated satellites launched by others. Loverro and other officials, helped by Representatives Mike Rogers of Alabama and Jim Cooper of Tennessee, both on the House Armed Services Committee, kept pushing for a space branch of the military and got nowhere until December 2019, when Space Force was created by presidential fiat. "Magically, we were revived," Loverro says.

This suddenness meant that for a while, Space Force was long on rhetoric but short on specifics and subject to snide remarks from people on the Internet. Its public image was not helped when its first official act was to design uniforms (camouflage, even for soldiers whose field of battle is in front of a computer) and a logo (the delta-shaped wing shared by patches of the U.S. Air Force and the National Reconnaissance Office—and *Star Trek*). By June, however, Space Force and its Combatant Command, U.S. Space Command, were recruiting tech-smart people; coordinating with international allies; deciding which technologies to buy; and running war-game simulations in which teams attack, counterattack and outthink one another. Space war "doesn't have to be inevitable," says Brigadier General Thomas James, commander at Joint Task Force–Space Defense, a component of Space Command, but "it's very serious business, and we take it seriously."

OFFENSE AND DEFENSE

ANYONE ATTACKING SATELLITES can choose from a long, varied menu of weapons. The splashiest option, called a direct-ascent antisatellite weapon, or DA-ASAT, is a missile shot from Earth that blows up a spacecraft. The U.S. and Russia have had DA-ASAT missiles since the cold war. China and India have both tested DA-ASATs on their own satellites. Russia's latest test was this past April.

Another option for attacking satellites is a maneuverable satellite, like Cosmos 2542, which can approach another country's vehicle. Satellites have often used small engines to move for safety reasons, such as to avoid space debris, and maneuverable satellites could be used for refueling or repair. But maneuverable satellites can be dual use, equally capable of colliding with other satellites or of spying on or shooting them. In the past few years the U.S. and Russia have used satellites to deploy smaller subsatellites that roam around: Cosmos 2542 emitted Cosmos 2543, which also stalked USA 245. The U.S. has the X-37B, a smaller, robotic version of the Space Shuttle that does generally secret things, including emitting subsatellites. What these subsatellites can do that parent satellites cannot is also secret and therefore unclear: Weeden says that all we know about them is what we see.

A space war technology that we cannot see, in contrast, is electromagnetic radiation. Satellites can carry equipment to jam others' communications from or to ground stations, or they can mount spoofing attacks to trick other satellites into communicating the wrong things. The U.S., China and Russia routinely jam other countries' links with navigation satellites. Lasers on satellites or on the ground can dazzle or blind spy satellites' imaging sensors, although exactly who has what laser technology with which capabilities is, again, classified or unknown.

In all these hostilities, the U.S. has much to lose. Of the 3,200 or so functioning satellites, the U.S. owns 1,327. Of those, 935 are commercial satellites that provide broadcasting and secure, global communications. Around 200 U.S. satellites are government and scientific satellites that collect data for predicting hurricanes, monitoring droughts, watching the creep of continents and, like the Hubble Space Telescope, understanding the universe. The remaining handful are military and intelligence satellites, most of which are used for communications—command and control of forces, for example, or directing of drones—and for spying. Together the satellites enable modern civilization. They provide the Internet access and GPS navigation and timing signals on which everyone in the world depends and support industries from banking to food supply, the power grid, transportation, the news media and health care.

The few military and intelligence satellites are fundamental to U.S. security and are the source of its vulnerability. The early-missile-warning system uses only 10 satellites, the intelligence community's high-resolution imagery is provided by maybe a dozen, and military command and control communications depend on just six. "The central military problem has been," Grego says, "that we extended ourselves into space, and now we're vulnerable."

This vulnerability matters because no one is sure how satellites can be defended. Perhaps imaging satellites could be fitted with a shutter that reacts fast to too much light, or bodyguard satellites could protect other satellites. Whether such defenses have been put into practice is unknown. "You won't find a lot of official details on the technologies for defense," Weeden says, "due to classification." "Cloaking" a satellite is technically possible, he says, but also expensive and difficult. You can make a spacecraft dark to radar or to telescopes but not to both, and the process can hamper the satellite's performance.

Most efforts at defense tend to focus on deterrence. "The natural place for the military to go is deterrence by punishment," Grego says. "You use ASAT on me; I'll use it on you." The first prob-