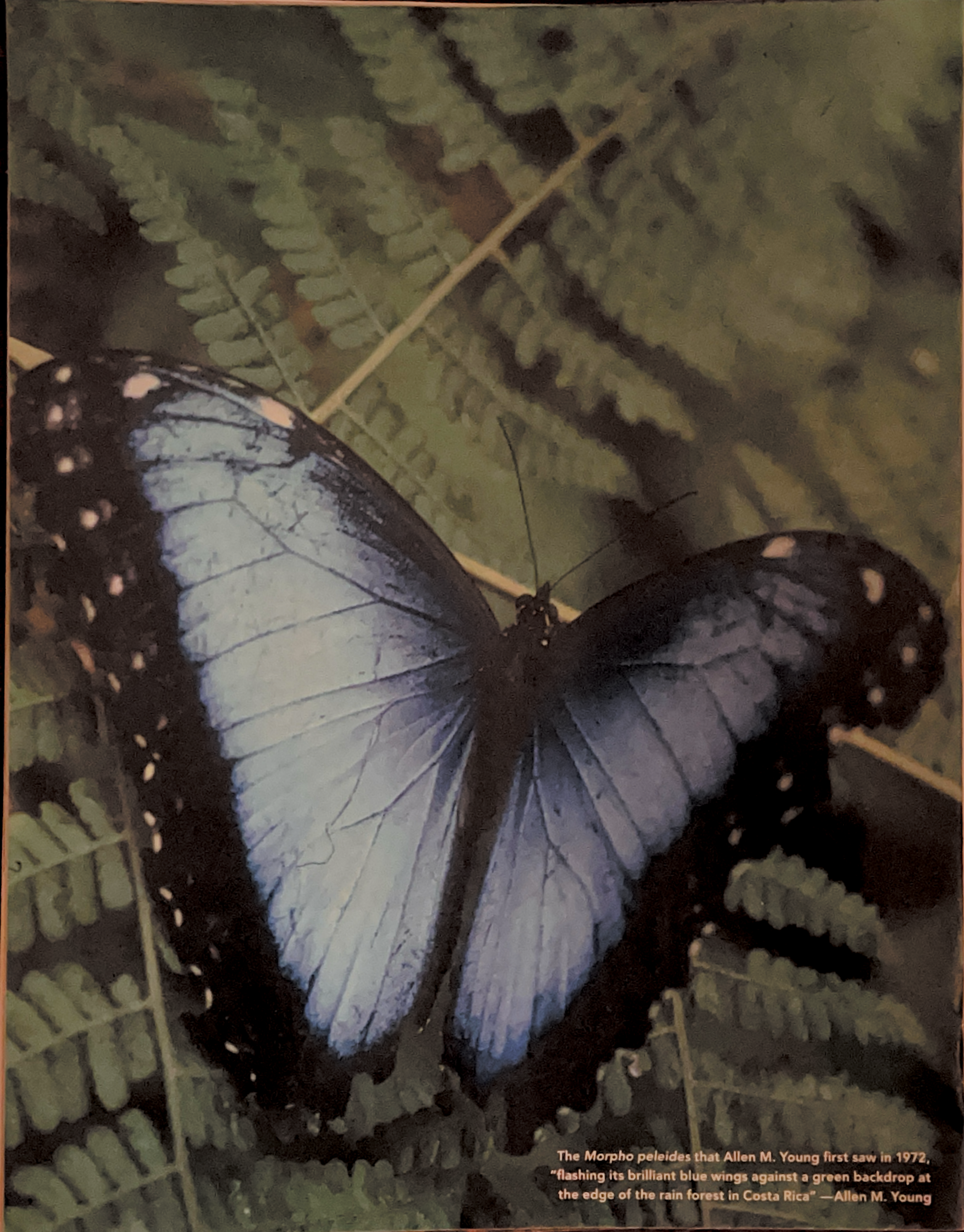




The *Morpho peleides* that Allen M. Young first saw in 1972, "flashing its brilliant blue wings against a green backdrop at the edge of the rain forest in Costa Rica" —Allen M. Young

THE VALUE OF BASIC RESEARCH

How the wonder of a blue butterfly inspired modern innovation

EMILIE C. SNELL-ROOD

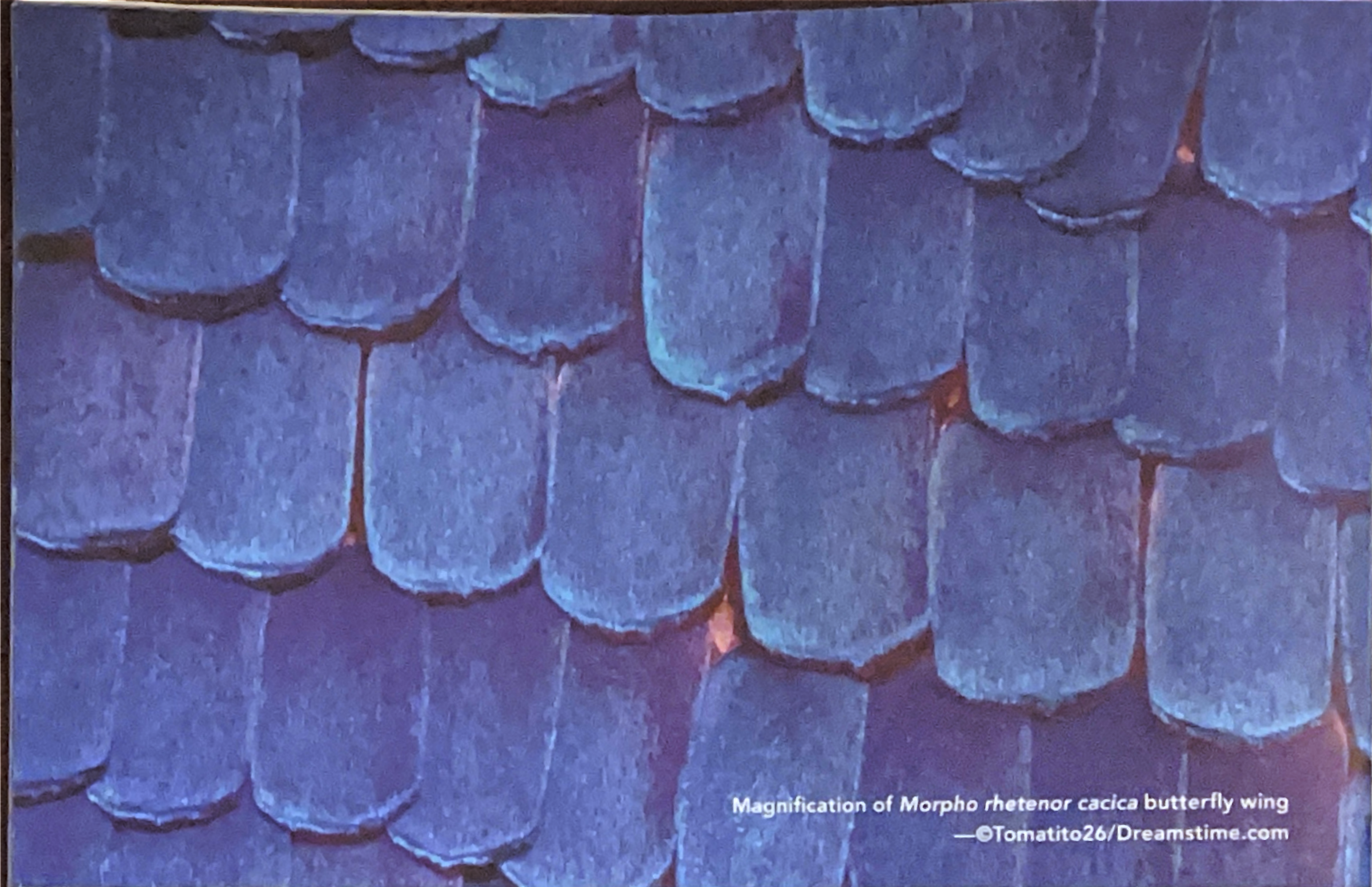
ACADEMIC INSTITUTIONS and funders of science have a long history of appreciating and supporting basic research. Studies have repeatedly shown economic payoffs of investing in basic research, alongside lists of specific patents, products, and applications generating benefits to society. And yet, government attacks on basic research, and even on the scientific process itself, seem unending. For example, there have been recent calls to shift the focus of basic research funding in the United States to “artificial intelligence, quantum information science, biotechnology, nuclear energy, and translational science.” The use of data to counter anti-science arguments has only limited success in highly politicized settings. Some have argued that storytelling approaches can be just as effective in science communication. Here—reprinted from a paper I first published earlier this year in the *Journal of Experimental Biology*—I use such an approach to trace the history of one set of biomimetic applications from present-day uses to the foundation of knowledge that was laid decades to centuries prior. Across these examples, I ask why researchers were drawn to the focal species—the answer usually relates to curiosity or wonder about the organism—and what this means for how we structure basic research. I use the *Morpho* butterfly (family Nymphalidae) as a case study, as it is one of the classic examples of applications inspired by biological traits, and it is an example where we can follow the literature back hundreds of years. However, one could easily write an entire book of comparative examples; for instance, using gecko feet, spider silk, or bird wings. This “Perspective” is not meant as a thorough review of *Morpho* butterfly biology, but as a “highlight reel” of research, including both early work and that of a few of the most prolific *Morpho* researchers.

FROM ROBOTS TO MATERIALS, the biomimetic approach seeks to emulate aspects of how biological traits work in our own design and engineering. A classic example of this approach is the inspiration taken from the bright blue structural color of the wings of butterflies in the genus *Morpho*. Structural color emerges from the manipulation of light by microscopic structures, in contrast to color

resulting from pigments differentially absorbing and reflecting certain wavelengths. The nanostructure of wing scales has inspired novel designs of sensors, photocatalyst structures on buildings, and radiative cooling technology. Our understanding of this biology has also led to improved light transmission of windows and even anti-counterfeiting materials. Some of the earliest attempts to physically copy this structural color came through the work of gastroenterologist Akira Saito, at Indiana University School of Medicine. Starting in the early 2000s, Saito developed methods of lithography to duplicate the nanostructure of *Morpho* wings.

Saito was bridging biology and engineering just as the term “biomimicry” was beginning to be popularized. What drew him to *Morpho* butterflies in the first place? As a child, he was an insect enthusiast. He was drawn to physics as a teenager but then rediscovered insects in graduate school through some popular books. Then, in 1997, he heard about an optical hypothesis for *Morpho* coloration at a physics conference and his interest was sparked. He plunged into the literature and saw that physicists had been interested in the optical properties of insects for over a century. He was encouraged by the fact that the preeminent scientists in the field found the topic interesting, but he was also concerned that perhaps everything had already been worked out. Saito soon realized there was still much to study, especially with respect to how to duplicate the underlying mechanism in our own technology.

ONE SCIENTIST IN THE EARLY GROUP OF researchers to consider *Morpho* butterflies—and inspire that first wave of applied research—was third Baron Rayleigh (John Strutt, 1842–1919), an inexhaustibly curious physicist interested in optics, acoustics and chemistry. Rayleigh is known for many phenomena that now bear his name (e.g. Rayleigh scattering, Rayleigh waves, the Rayleigh number) and for the discovery of argon. Of his many passions, he was driven to understand light, optics, and vision, his biography highlights his wonderings about why the sky (and water) are blue, why we see (or don’t see) in color, and why leaves soaked in liquid fluoresce red.



Magnification of *Morpho rhetenor cacica* butterfly wing

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He dabbled periodically in the curiosities of color in insects, first in the 1880s and then later in his life, when, according to his son, he felt he could work more freely. In a paper finished six months before his death, he wrote about the blues of *Morpho* scales and the greens of wings from beetles he collected in his garden—he questioned claims that pigments underlay these colors and explored the idea of structural color, concluding there was still much to learn. This line of inquiry was continued by others, such as chemical engineer Clyde W. Mason (1898–1983) at Cornell University and Rayleigh's son, Robert Strutt (the fourth Baron Rayleigh, 1875–1947), who more conclusively demonstrated that these colors were structural. The first scanning electron microscopy views of *Morpho* wing nanostructures in the early 1940s shed further light on how the structural colors were produced; this investigation also appeared to be curiosity driven, apparently motivated primarily by a desire to investigate interesting and diverse materials using an exciting new technology.

Exactly how these early researchers were drawn to include *Morpho* butterflies in their studies will probably never be known. Perhaps Lord Rayleigh was exposed to various *Morpho* species in a cabinet of curiosities or in a 1705 volume of Maria Sibylla Merian (1647–1717)'s

engravings of the *Morpho* life cycle in Surinam. Indeed, this popular book, along with the collection of the Swedish Queen Ulrika (1688–1741), served as the basis for Linnaeus' initial description of the *Morpho* genus in the 1750s (the names were inspired by characters of the Iliad, and *Morpho* was probably chosen to represent a 'kingly' genus; Sjöberg, 2008). Collectors were obsessed with *Morpho* butterflies—at times, there were over 750 taxonomic divisions of this group (relative to the approximately thirty species) which further fueled the hype over this genus. Despite the collecting fury, only select pieces of *Morpho* natural history were to be found in the literature. Merian, for example, had a lifelong passion for observing the life cycles of insects, dispelling the notion they spontaneously arose from mud. Although she was able to observe *Morpho* life stages with the help of Surinam locals, a more complete understanding of the natural history of this group did not make it into the literature until the 1970s, with the work of Allen M. Young, then a post-doctoral researcher with the Organization for Tropical Studies.

Young still vividly recalls the day in 1972 when he first saw a *Morpho peleides* flashing its brilliant blue wings against a green backdrop at the edge of the rainforest in Costa Rica (see "*Morphos and Me*" by Allen M. Young,

Natural History, February 2018). He was initially drawn to their beauty but soon found that studying their natural history was like “unraveling a mystery...with the biologist as the detective.” Young followed egg-laying females in the field, recorded caterpillar feeding behavior every hour for weeks, and marked (and re-sighted) hundreds of individuals at rotting fruit baits. He found that the more common species (*M. peleides*) lays eggs on a range of vines in the legume family, whereas other species are more specialized, some laying eggs on plants in an entirely different family (Sapindaceae) that overlaps in one chemical class. He surmised on the function of the blue coloration in deterring predators, explored the role of agriculture in creating islands of rainforest habitat that trap populations, and described how caterpillar movement away from their host plants during the day might reduce parasitism. Young was not the only researcher during this time driven to

understand *Morpho* biology. He tells the story of meeting Alberto Muyschondt, who owned and operated a gas station in El Salvador but was so in love with these butterflies that he had converted his office into a caterpillar nursery. Muyschondt went on to publish over thirty-five papers on the biology of *Morpho* and other tropical butterflies (several of his early publications being in collaboration with Young, (e.g., Young and Muyschondt, 1972).

WHEN SAITO STARTED TRYING to duplicate *Morpho* wings in the early 2000s, there was a rich base of knowledge on the genus, not only information on the physics of their wing reflection and their biology in the field but also an understanding of relationships across species and even their palatability to predators. However, much more research and development was necessary to move from these early investigations to today’s



Morpho menelaus



Morpho helenor



Morpho cypris



Morpho rhetenor



Morpho sulkowskyi



Morpho hecuba

Diversity of the butterfly genus *Morpho* —Emilie Snell-Rood

applications, spurring hundreds of studies in physics and optical engineering. The devil's advocate might ask "do we really need to know what a caterpillar eats for the application—once we have the wing, isn't it just an engineering problem?" Perhaps. But for a scientist to rear a butterfly, maybe to gain additional insights from the development of the trait, much more needs to be known about the biology. And any application is going to start with some initial spark from an initial observation. Although it is not necessary to know every aspect of *Morpho* anti-predatory behavior to build an anti-counterfeiting film inspired by their wings, those observations may form the basis for an entirely different line of applications. For instance, while in the field, Young noticed that *Morpho* butterflies are able to sip very sticky sap, and surmised that they may excrete some enzyme that decreases the viscosity of the liquid—such an observation could be the first step in the discovery of a new chemical application, but it is impossible to know where to look without the basic biology.

What does the above discussion teach us about the value of basic research? An auditor evaluating the payoff of science and research might look at the windows, fabrics, and screens inspired by *Morpho* wings and argue that investment should be focused on this application development stage. However, that tabulation would miss the key investments in the basic research that laid the groundwork. Today, federal, state, and private funding supports this basic research. Indeed, much of Young's work in the 1970s was funded by the United States National Science Foundation (NSF) and National Academy of Sciences, along with his own academic institution. Similarly, Saito et al.'s *Morpho* research was supported by the Ministry of Education, Culture, Sports, Science and Technology, one of the eleven ministries of the executive branch of government in Japan. Prior to the establishment of such funding agencies (e.g. the NSF was started in 1950), basic research was more limited to the wealthy or to those who could secure funds from wealthy patrons or scientific societies. For instance, Lord Rayleigh inherited a 7,000-acre estate, which was the primary source of his family's wealth, while Linnaeus relied on funds from rich benefactors (e.g. the royal inspector of a copper mine) or from the Royal Swedish Society of Sciences. At the other end of the spectrum, Maria Sibylla Merian struggled to get by much of her life, surviving off the sales of her artwork, as her family was not wealthy and women had no avenues into science at the time. Although she was destitute at the time of her death, ironically, the first edition of her book can now sell for USD \$200,000–600,000.

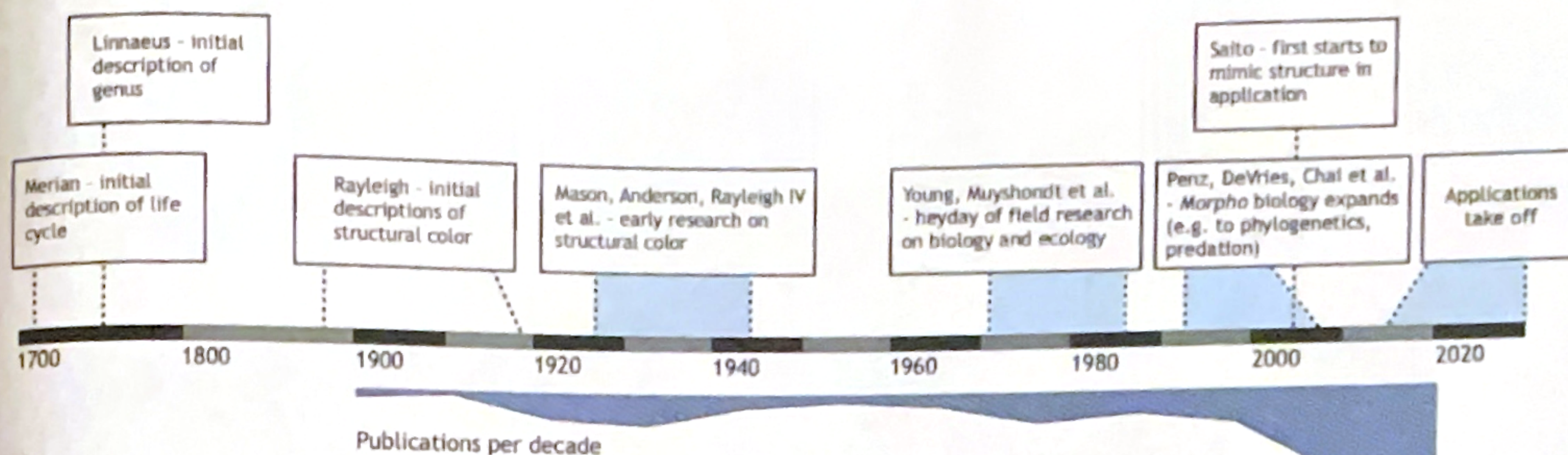
The society that funds basic research not only invests in the base of knowledge that drives innovation for centuries to come but also supports a more diverse and equitable population of scientists. Studies that have attempted to

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quantify the return-on-investment of public dollars into funding basic research show an average payoff of at least 50 percent. But these studies are often focused on more tangible deliverables, such as novel drugs and the research that funded their development. It is challenging to quantify the long-term value of a basic natural history description of a blue *Morpho* butterfly, something the NSF funded in the 1970s, but likely would not fund under new directorates that propose to focus on more applied fields. Are we returning to a time when only those with a private estate can fund their own curiosity-driven research, while the 'Merians' of the world must scrape by to pursue their questions? Government and institutional support of basic research has allowed more equitable access to science over the last several decades, expanding the number of scientists who are of diverse financial, ethnic, geographic, and gender backgrounds. For instance, in the US since the early 1980s, the number of citizens from minority backgrounds earning doctorates in science and engineering fields has doubled, along with a 50 percent and 140 percent increase in doctorates awarded to women and international students, respectively. Although the scientific workforce does not yet match the diversity of the public, it has come a long way since the days of Rayleigh, through public support for basic research.

THESE STORIES OF SCIENTISTS, from Merian and Rayleigh to Young and Muyschondt to Saito, illustrate not only the value of basic research but also the role of wonder and curiosity in drawing the researcher into a study.

In a world often driven by application and profit, how do we as scientists and as a broader society allow space and opportunity for observation and basic research? How do we nurture inquiry, but also encourage such questioning to explore every aspect of the tree of life? *Morpho* butterflies are big and flashy, and thus have long been common features in museums. How do we fall in love with the small species, the hidden organisms, or the slimy or "ugly" ones? Fortunately, observation tends to beget curiosity. Our first question leads to twenty more. As we learn about a species (even the slimy ones), we develop a fondness for them, which fosters that bedrock of basic research, resulting in a foundation for future applications.



Timeline of selected research on *Morpho* butterflies. The upper panel shows a summary of the researchers highlighted in this Perspective, with the applications not starting until the 2000s. Light blue shading indicates a range of dates, whereas single black lines indicate one date. The lower panel shows the approximate rate of publications on *Morpho* butterflies, per decade of the 1900s to 2020 [using the search term 'Morpho and (butterfl* or Lepidopt*)' in Web of Science].

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At the same time, we might ask how we best invest our basic research when there are likely to be over 10 million species on Earth. Should we renew efforts to study understudied branches of the tree of life? This approach would lead to us investing more in research on invertebrates and microbes. Perhaps we should focus on biological models that, through evolution, have already solved problems that are analogous to our own? For instance, if we wish to find biological traits that are effective at capturing or reflecting light under low-light conditions, we might look to organisms doing just that on the rainforest floor or during twilight hours. Or maybe we are more likely to stumble on an application when studying species that inhabit particularly challenging or extreme environments: the PCR-based revolution in molecular genetics was made possible by the discovery of microbes adapted to extreme heat environments. These examples represent basic research that is narrowed somewhat by the search for specific inspiration—what some have called “use-inspired basic research,” a middle ground between purely applied and purely basic research.

How we direct our basic research efforts is an important discussion to have within fields, funding agencies, and as a society interested in conservation of biodiversity and innovative applications. Perhaps we need to renew efforts to support natural history research and descriptive observation of biodiversity through funding and publishing opportunities. Or maybe we should expand mechanisms for community scientists to report natural history observations on platforms such as iNaturalist. Maybe we need to reconsider how to foster asking questions in our education system, rather than focusing on the right answers on

standardized tests. Regardless, we are at a nexus where we need wider discussions on the landscape of science.

WE CAN TAKE A FEW IMPORTANT LESSONS from the story of the *Morpho* butterfly and how a fascination with a beautiful creature eventually inspired applications in many fields seeking to manipulate and control light. People are drawn to ask questions and try to understand nature—when they are given the freedom and resources to pursue knowledge, we benefit as a society. We have millions of incredible species to learn from; the basic knowledge that results can potentially help us solve problems in the future. We are richer with the knowledge of why the birds sing early and the butterflies are bright blue. Feeding that curiosity is not only deeply satisfying but also forms the basis of innovation and application for years to come.

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