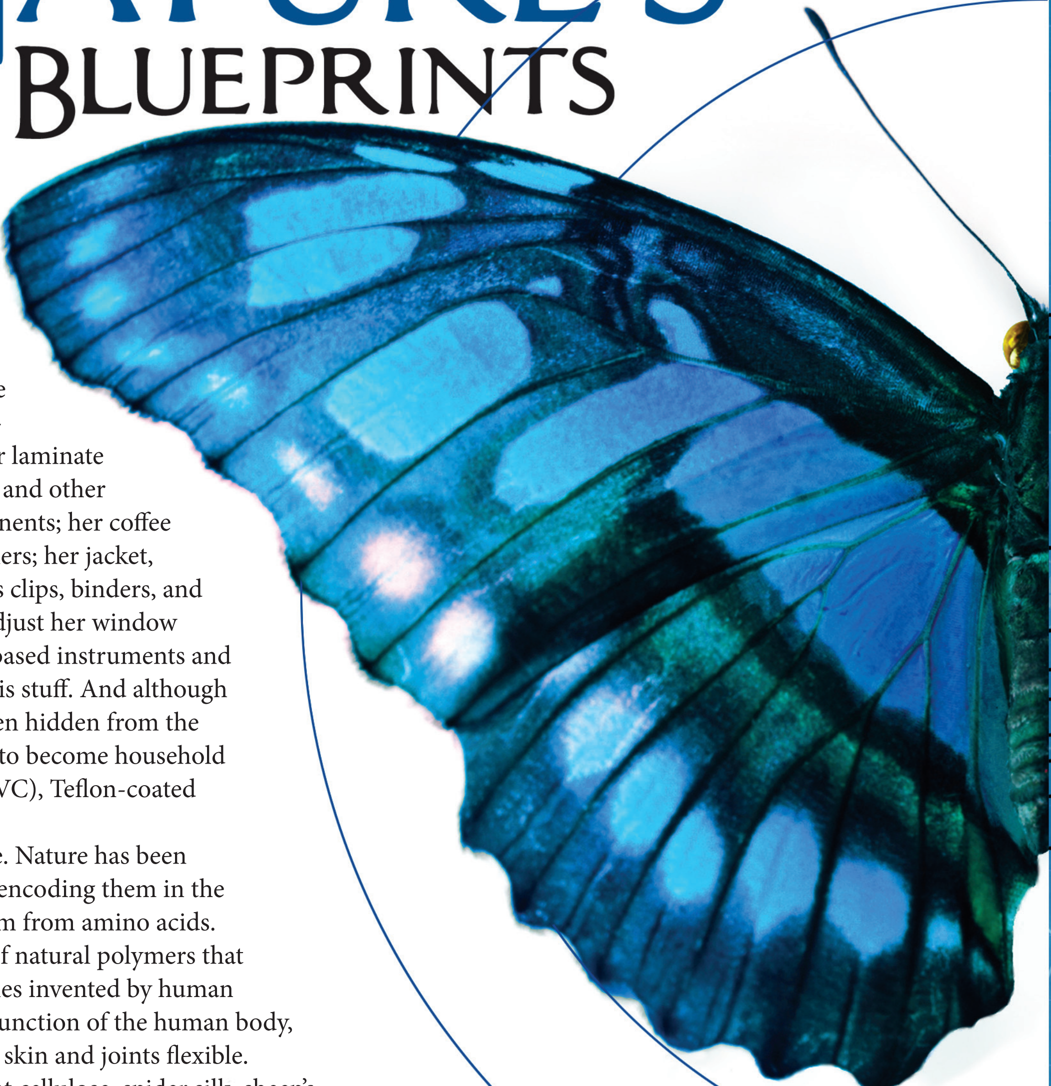
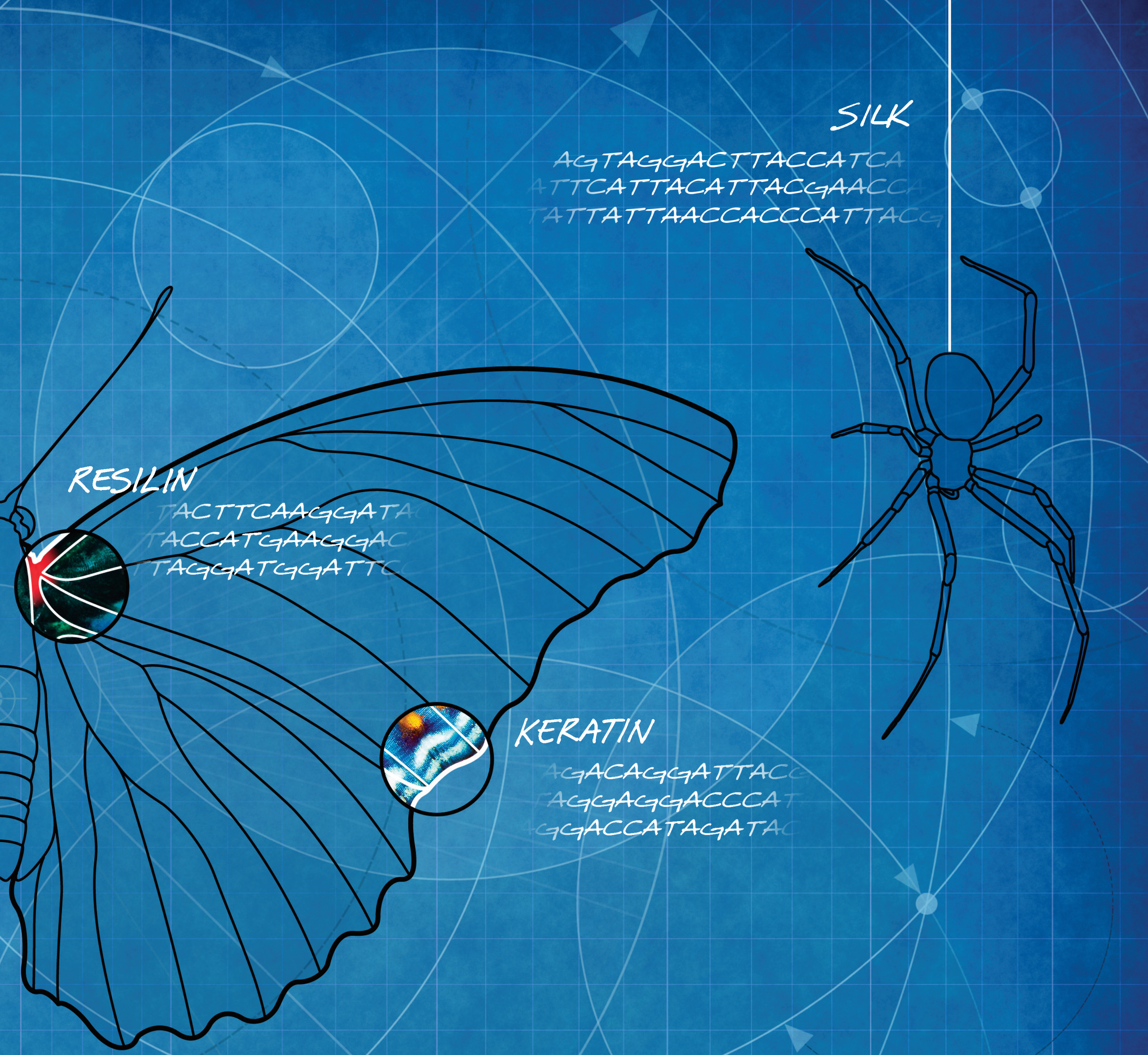
BORROWING NATURE'S BLUEPRINTS



"WE CAN'T DRIVE, we can't eat, we can't do much of anything without polymers," says Jennifer Martinez, a chemist with the Center for Integrated Nanotechnologies (CINT) at Los Alamos. She casually gestures at the multitude of polymer-containing objects within her own office—her laminate desk and plastic chairs; her phone, computer, and other devices, as well as their many internal components; her coffee thermos and assorted food and drink containers; her jacket, sunglasses, wristwatch, and shoes; the various clips, binders, and dispensers all around; and even the cord to adjust her window blinds. Then there's the plethora of polymer-based instruments and processes that went into manufacturing all this stuff. And although the pervasive use of synthetic polymers is often hidden from the average person, a few of them have managed to become household names, including polyvinyl chloride pipes (PVC), Teflon-coated pans, and nylon fabrics.

Yet polymers weren't invented by people. Nature has been using them much longer than humanity has, encoding them in the DNA of living organisms and assembling them from amino acids. In fact, evolution happened upon a number of natural polymers that are in many ways superior to the synthetic ones invented by human engineers. Some polymers are critical to the function of the human body, such as the elastin and collagen that keep our skin and joints flexible. Others are only found elsewhere, such as plant cellulose, spider silk, sheep's wool, or bioluminescent proteins from jellyfish. They are in blood vessels and bones, toenails and teeth, stalks and stems, hooves and horns, feathers and fur.

These natural polymers are valuable in their own right, but they also provide key inspiration to help scientists and engineers combine or improve upon their attributes for human use. Indeed, one of the earliest manmade polymers, the fabric rayon, was inspired by natural silk and made from the cellulose in wood pulp more than 100 years ago. Now, modern genetic tools stand poised to create perhaps hundreds of highly advanced synthetic polymers for mechanical and biological applications of all kinds. And researchers like Martinez are counting on nature to show them the way.



LOS ALAMOS SCIENTISTS ARE LEARNING TO MIMIC SOME OF NATURE'S GREATEST MATERIALS-SCIENCE INVENTIONS—AND IMPROVE UPON THEM.

Poly sci

Technically, a polymer is any large molecule formed as a sequence of repeated subunits. In a biological context, the subunits are generally simple biomolecules, such as sugars, fats, and amino acids, which can be arrayed into polymers called polysaccharides, lipids, and proteins, respectively. The subunits might also be nucleotides, in which case the polymer would be RNA or DNA. Or the subunits might be a variation on one of these themes. Synthetic polymers, too, are arrangements of different kinds of chemical subunits with varying complexity. The relatively simple synthetic polymer polypropylene, for example, is a common plastic with a subunit that's just a particular arrangement of three carbon atoms and six hydrogen atoms, nothing more.

Martinez is interested in simple proteins made from a specific sequence of 10 or 15 amino acids, say, repeated perhaps 100 times. Unlike more complex proteins, such as enzymes, that can contain tens of thousands of amino acids in a precise sequence, her preferred proteins are essentially polymers *of* polymers: repeating sequences of short amino-acid sequences. Yet even these relatively simple sequences can get out of control quickly. Out of 20 varieties of amino acids, even a sequence of just five of them allows for 20^5 or 20 × 20 × 20 × 20 × 20 combinations—that's over three million possibilities. So the problem of designing polymers would be instantly unwieldy without some kind of starting point.

In living cells, that starting point is the genetic code. DNA carries the exact instruction sequence for arranging amino acids into proteins. Following suit, Martinez begins with known sequences of DNA that encode for proteins with valuable properties, and to those sequences she adds some closely related sequences with targeted variations in order to look for potential improvements on nature's original designs. She then employs a variety of laboratory techniques, working with viruses, bacteria, and yeast, to read the DNA segments and assemble the corresponding proteins. Finally, calling upon a suite of sophisticated screening protocols that sort by temperature effects, fluorescence, pressure response, and other attributes, she screens her proteins for any that possess the desired properties. From there, she can tweak, refine, and repeat her way to material perfection.

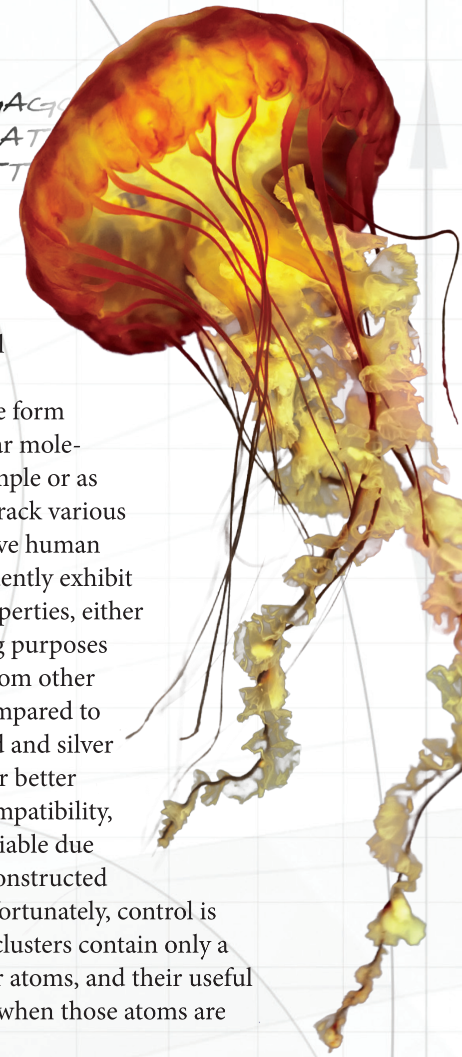
Inspired by nature

Natural polymers do some remarkable things. Take something as seemingly simple as human skin, for example. More than 75 percent of it is composed of collagen, in addition to elastin. Together, these two polymers give skin its strength, insulating properties, and tremendous flexibility—and allow it to ward off sagging and wrinkling for as long as the body is able to produce enough of them. The polymers also enable nerves to deliver sophisticated pressure sensitivity, allowing them to sense varying degrees of compression, stretching, twisting, and so forth. In addition, they form a barrier that is waterproof (and, therefore, largely pathogen-proof) from the outside but can secrete sweat at a regulated, adjustable rate from the inside. They allow for self-healing, with more collagen produced during wound repair. And another natural polymer in the skin, a common pigment called melanin, makes the skin optically responsive by absorbing harmful ultraviolet sunlight.

That's just human skin (and only a subset of its virtues at that). But nature has invented many other polymers with many other desirable attributes: the extreme tensile strength of spider silk and the insulating power of wool; the versatility of plant-based polymers, such as rubber and cotton; the optical iridescence of some beetles, bird feathers, and butterfly wings; the low-friction hardness of snake scales; the absorbency and transparency of jellyfish; and the adhesive properties of vegetable dextrin and boiled animal collagen (both used to make glue). All of these are purely natural resources derived from biological evolution, yet there is every reason to believe they can be improved by a deliberate human redesign.

Resilin, for example, is the enormously elastic protein responsible for the spring action of rapidly beating insect wings or jumping fleas. It is incredibly efficient at producing rebound motion without losing energy to heat and doesn't substantially degrade even after hundreds of millions of expansion-compression cycles. An Australian team recently extracted the gene for it from a fruit fly and re-expressed that gene in a laboratory setting. With some modifications, they developed a synthetic resilin that may find a home in a wide variety of applications, from athletic shoes to spinal implants.

Martinez anticipates many more revolutionary materials to be made possible by genetically engineering polymers. She is particularly motivated by the possibility of isolating the genetic sequences associated with various desirable attributes and then combining them in novel ways to make multifunctional materials.



"Suppose you could combine the optical glow from a bioluminescent fish with the pressure sensitivity of animal skins," says Martinez. "You can imagine engineering a new kind of flexible touch-screen that responds to different amounts of pressure by emitting different kinds of light. Or you could make a flexible body armor by combining the strength and elasticity of different natural polymers. Or you could engineer fiber-forming polymers with particular optical properties to make a solar energy-harvesting fabric. The possibilities are nearly endless. And that's not even considering the biomedical arena."

Replacement body parts

Because of their origins in living tissue, genetically encoded polymers naturally lend themselves to many potential biomedical applications. In the future, tooth fillings may no longer consist of foreign materials; they may instead consist of dentin that has been genetically designed to integrate with the tooth and accommodate new enamel. And bypass surgery to save a heart-attack patient may no longer require a real blood vessel grafted from the patient's arm or leg; it may instead be possible to construct an actual replacement blood vessel with genetically encoded polymers. That blood vessel could then trigger the growth of endothelial cells to line its interior and heal its own surgical seams.

"One of my favorite examples to illustrate the potential of genetically encoded materials is sprayable skin," says Martinez. Rather than treating a wound, possibly a very deep one, with a bandage, she envisions spraying a polymer that has been designed to seal the wound with a strong, flexible, and yet artificial skin. It would be largely based on the skin's natural collagen and would even produce the correct biochemical and mechanical cues to hasten the body's natural healing mechanisms by recruiting the correct sequence of cells. The wounded individual could then return to normal activity, fully protected, while the healing continues under the skin. "Inventing sprayable skin will require a lot of hard work by a lot of smart people," she says, "but there's nothing fundamentally preventing it."

Most of the new materials for products and biomedical uses are still a ways off. Right now, Martinez is working to develop the underlying techniques for creating genetically encoded polymers with valuable materials properties. Despite early indications of success, including polymers designed to control the fate of cells and others to act as fluorescing strain sensors, her efforts to make the physical materials of the future will take place mostly, well, in the future—with an interesting exception.

New twist

Biosensors are important in biomedical research and diagnostic imaging. Whether in the form of tags to track particular molecules in a laboratory sample or as implantable devices to track various health indicators in active human beings, biosensors frequently exhibit optical fluorescence properties, either to emit light for imaging purposes or to detect it coming from other emitting molecules. Compared to existing biosensors, gold and silver nanocluster devices offer better performance and biocompatibility, yet have remained nonviable due to their inability to be constructed in a controlled way. Unfortunately, control is key because these nanoclusters contain only a few tens of gold or silver atoms, and their useful properties emerge only when those atoms are properly arranged.

Martinez obtained the necessary control over nanocluster construction with the quintessential natural polymer: DNA. She and Los Alamos colleague James Werner designed and constructed specific DNA snippets to serve as scaffolding for the gold and silver atoms. They were then able to control the atoms' clustering by controlling the DNA code. The resulting nanoclusters may be used for biosensing, including national security applications such as detecting biothreat agents, and may even improve upon existing nanotechnology for solar energy harvesting.

Yet such DNA scaffolding probably only represents the low-hanging fruit of the smart-polymer orchard. Martinez believes she and others will make the most profound polymer advances simply by mimicking and tweaking polymers already invented by nature. But does that make her feel unoriginal?

"Not at all," she says. "There's no shame in mimicking nature. It had a billion-year head start after all. But we're catching up now." LDRD

—Craig Tyler