The Mighty Gossamer

Fritz Vollrath

The silken threads of a spider's web are stronger than steel.

Four and a half thousand years ago, little Si-Ling-Shi of the southern capital of Hang-Chow-Foo discovered silk. Or so the legend goes. The princess, who later became goddess of the Chinese silk industry, happened to observe a small caterpillar spinning its cocoon. She noticed that the cocoon consisted of a single thread and realized that unraveling the silken structure would yield a thread that, bundled together with many others, could be used to spin the most exquisite of garments. And so they were, of a luster and strength unrivaled until the development of the first man-made polymer plastics, not so long ago.

Soon, silk may have its comeback: Genetic engineers claim to have inserted silk genes into bacteria and are waiting only for the machinery necessary to express this bacterial silk into fibers. However, this new, artificial silk is not modeled on the silk of *Bombyx mori*, the lepidopteran caterpillar observed by Si-Ling-Shi but on that of the garden spider, *Araneus diadematus*, and the gigantic golden orb spider, *Nephila clavipes*.

Spiderweb silk must be strong enough to halt an insect in midair; it must be thin to minimize the spider's expenditure of protein; and it must be of even diameter throughout, as otherwise the entire thread will break. However, a spider produces more than one kind of silk, and not all of them are used in her web. One sort functions like silkworm fibers, providing the tough covering of the little sac that contains the spider's eggs. Another silk has a double function; fluffed up, it cradles the delicate eggs, but when paid out in ribbons it entangles and enshrouds the unfortunate prey insect. Being a shrewd economist, the spider actually puts most of its silk to double duty: The safety line, trailed at all times, doubles up as the material for the frames and radials of the web. The cement that anchors lines to the ground also binds the crisscrossing strands of the egg sac and fixes the spirals onto the supporting radials.

Each of the silks is marvelously adapted to its particular job or jobs. This is not surprising if one considers the 400 million years or so during which spider silk evolved from the relatively simple silk of the tarantula to the highly specialized varieties of the modern orb web spider. As they emerged in the Cretaceous, circa 180 million years ago, orb spiders like *Araneus* have had many generations to fine-tune each and every one of their silks. Thus their webs have become veritable showpieces for the adaptedness of a material and its economic use.

Unlike the caterpillar's silk, which provides a tough protective cover made once in a lifetime, spiderweb silks are respun daily, often in large quantities. They are thin enough to be practically invisible, yet they are strong enough to catch insects in full flight. This is no mean feat considering that, pound for pound, the kinetic energy to be absorbed exceeds the impact of a jet landing on an aircraft carrier. Some of that energy is deflected by the web's architecture, but most is absorbed by the material itself. And a very adaptable material it is.

Protein matrix

Silk, be it spun by spider, moth, or mite, is basically one and the same material. Actually, it is not strictly correct to speak of silk as a material. It is a composite consisting of protein crystals embedded in a protein matrix—not unlike wattle and daub or glass fiber, with its fibers of glass embedded in a matrix of resin. The silk's crystals are sheets of interlinked amino acids, stacked like a pile of corrugated iron sheets. Amino acids are the building blocks that, firmly interlinked into chains and nets, make up a protein. The crystals they constitute give the silk thread its strength. This strength is largely determined by the length, diameter, and composition of the crystals.

The great strength of a composite, as compared with a homogeneous material, derives from its ability to deflect a crack. Cracks are the great enemy of a material under tension. This is because the stress lines that normally run parallel bunch up at the tip of the crack, creating a greater load and thus propagating the crack with ever-increasing speed and force. In a composite material, the growing crack suddenly encounters an obstacle, whether it be a crystal, glass fiber, or wattle. Now it has no choice but to run around that obstacle along the interface of

■ ***An orb weaver spins a web with silks that behave differently. The radiating spokes are stiff, whereas the circumferential capture threads that they support are more elastic.***

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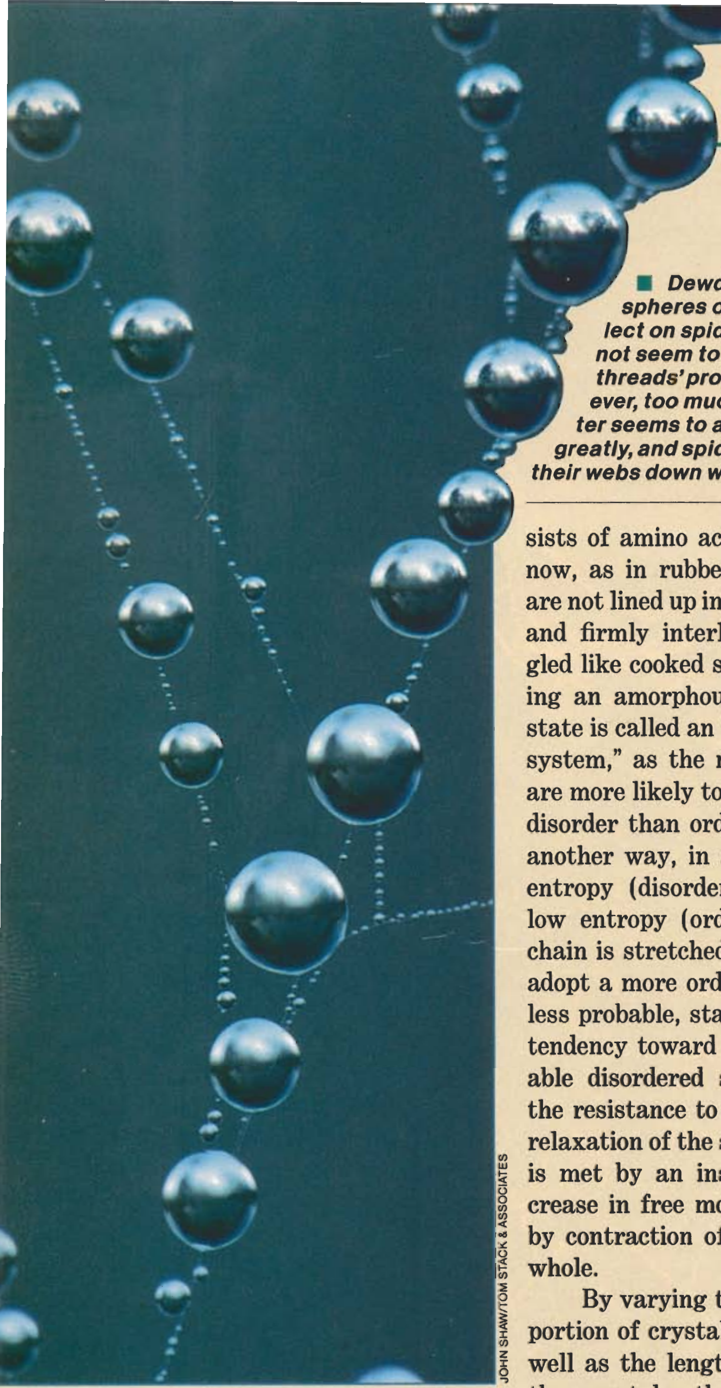

■ *Dewdrops (the large spheres on strands) collect on spiderwebs but do not seem to inhibit the threads' proper action. However, too much external water seems to affect the web greatly, and spiders always take their webs down when it rains.*

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the materials, a task that diverts and absorbs much of its energy. If it meets obstacle after obstacle, the crack quickly stops for good.

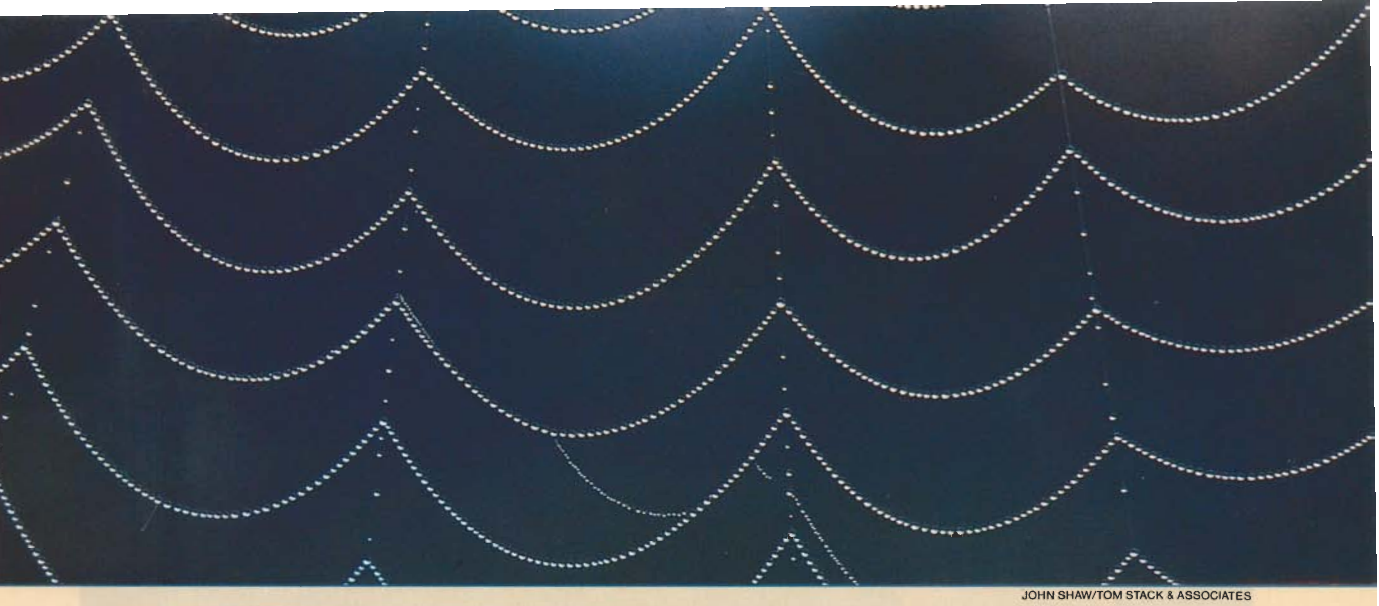
The protein matrix of the silk, which might be compared to rubber, gives the silk thread its elasticity. The matrix, too, consists of amino acid chains. Only now, as in rubber, these chains are not lined up in an orderly way and firmly interlinked but tangled like cooked spaghetti, forming an amorphous matrix. This state is called an "entropy driven system," as the molecule chains are more likely to be in a state of disorder than order or, to put it another way, in a state of high entropy (disorder) rather than low entropy (order). When the chain is stretched, it is forced to adopt a more orderly, and hence less probable, state. The natural tendency toward the more probable disordered states provides the resistance to extension. Any relaxation of the stretching force is met by an instantaneous increase in free motion and, thus, by contraction of the fiber as a whole.

By varying the relative proportion of crystals to matrix, as well as the length and width of the crystals, the spider easily changes the properties of its silk. It seems that the animal may use such adaptation in a direct and reflexlike response, for example, meeting an increased demand for strength on a windy day by varying the speed at which it pushes the silk through its spinnerets. Greater changes of material qualities seem to require a more fundamental change, this time in the chemical composition of the chains. And for this feat the spider has different glands producing different raw materials.

The spider's orb web incorporates silks of varied chemical composition and distinctive mechanical behavior, connected in a polar network that has both firm and soft sections. The firm sections, the radii, transmit the vibrations that signal the presence of prey; they also form pathways by which the spider traverses its web. Moreover, the radii support the capture spiral that forms the soft sections, which are sticky and extraordinarily elastic. Its softness prevents the capture spiral from interfering with the vibration transfer along the radii, which would be dampened by a tightly strung connection spiral. In addition, its softness is necessary to arrest the insect's flight without catapulting it back out, trampoline-fashion, or providing it with purchase for its struggling legs.

Sticky strands

Most of the victim's kinetic energy, however, is absorbed by the material itself, or, to be more precise, by the sticky strands. Here the composite silk is further modified into something that transcends a mere material and is better called a mechanism, albeit on a minute scale. The sticky strands consist of a pair of core


JOHN SHAW/TOM STACK & ASSOCIATES

■ ***Most of a victim's kinetic energy is absorbed by the sticky strands, which sag under the weight of a viscous coating.***

fibers surrounded by a coat of highly viscous, syrupy liquid. The liquid, although applied as a continuous film, quickly separates into droplets. It is a watery solution of very hygroscopic (water-attracting) chemicals. This liquid creeps into the silken core fibers, altering their mechanical behavior.

Whereas dry silk is rather stiff and breaks at extensions of 30 percent or so, waterlogged silk becomes floppy and elastic. The coated sticky spiral can be expanded by 400 percent or so, stretching four times its length before it breaks. In the initial phase little force is needed to stretch the thread, but after an extension of 300 percent it suddenly begins to resist further stretching. Although the sticky thread is soft and appears to require very little force to stretch, it is actually quite strong. But this strength only shows at the very end of its extension.

Just before breaking, it develops a great resistance to further stretching. Thus the sticky thread has the strength to retain the hapless prey without acting as a trampoline or vibration damper. The kinetic energy of the prey so suddenly stopped in midflight is converted into heat and distributed throughout the waterlogged threads. But since rubber-like materials develop greater rather than lesser strength when hot, this absorbed energy actually strengthens the thread. And, as we have seen, the potentially fatal cracks are checked by the crystals that reside in the rubber matrix.

When suddenly relaxed from a stretched position, dry silk sags and is very slow to creep back to its former length. The sticky threads snap back into shape instantaneously and, even more astonishing, can be relaxed far beyond their initial length without sagging. Amazing as it seems, the droplets act as tiny windlasses and cable drums, whereby the surface tension of the watery coat powers the reeling in of the core fibers. Stretching and relaxing a sticky thread in rapid succession will wind and unwind the core fibers inside their droplets. Thus the entire system of threads and coat is always under tension, keeping the sticky thread taut. The force energy applied by buffeting winds or blundering insects is, in this case, not absorbed by the silk itself but by the system. And very effectively absorbed it is too. What else do you expect of 180 million years of time spent on research and development?

Thus the spider has turned a great and potentially fatal disadvantage—namely, that silk becomes floppy when wet—into an advantage. It just coats with water those threads that ought to be soft without being weak. The strong, dry threads form the spider's highways and signal lines, the sticky, wet threads its network of snares. The spider's silken orb web is only one example of natural systems' ability to evolve amazing structures within the constraints imposed by raw materials. Maybe the spider can teach us a trick or two.■

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