

Nature's Blueprint

MIMICKING EVOLUTION'S CLEVEREST DESIGNS

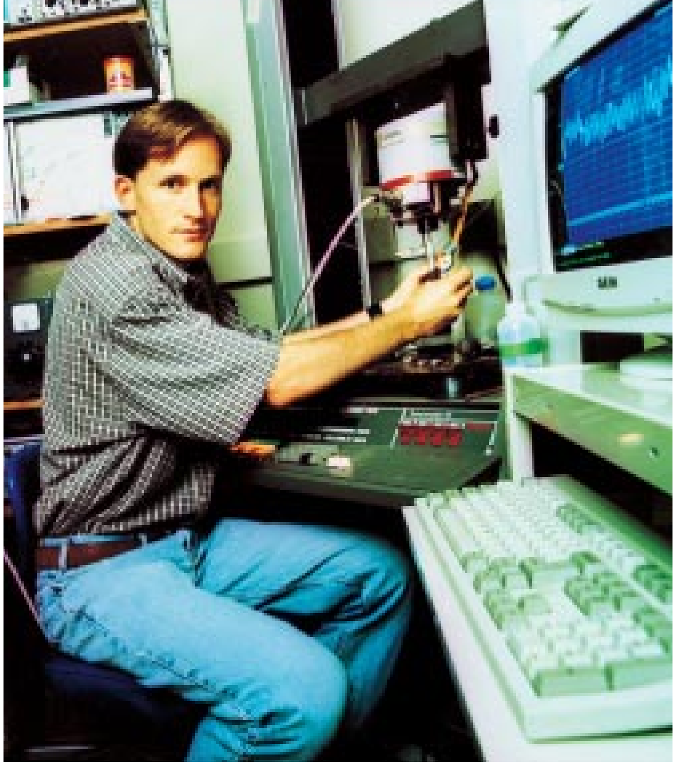
BY ROBERT MONROE

The story behind one of the most common household products goes like this. Swiss inventor George de Mestral was an avid hiker who grew tired of the plant burrs that stuck to his wool pants and to his shaggy dog's coat. One day in 1948, after a hike through France's Jura Mountains, he decided to examine the tiny tormentors further.

He noticed that the burrs contained hundreds of tiny hooks that grabbed clothing fibers or anything else they touched. It gave de Mestral an idea and in 1951, he patented his new invention: Velcro.

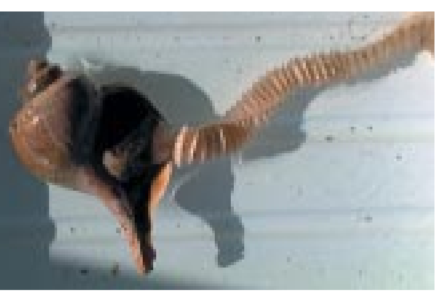
A similar story of discovery goes like this. A colleague of Scripps Institution of Oceanography researcher Robert Shadwick stumbled across sea snail egg capsules on a walk along a Delaware beach with his young son. The friend, a biochemist named Herb Waite, noticed how peculiarly elastic the capsules were when his son stretched them. He suggested that Shadwick figure out what made them so elastic yet so strong.

Scripps marine biologist Mark Hildebrand believes that the diatoms he cultures in the laboratory have nanotechnological secrets to reveal.



Shadwick, a marine biologist in the Marine Biology Research Division, assigned the project to graduate student Scott Rapoport, who found that Waite's observations were correct. The capsules could be stretched like a piece of taffy, but unlike the candy, would revert to their original shape no matter how many times they were pulled. The identification and synthetic production of such a substance could lead to a variety of applications.

The development of products from those egg capsules is still a long way off, but Rapoport's research, as well as that of Scripps marine biologist Mark Hildebrand, is evidence that even the most modest creatures have mechanical secrets worth investigating. A protein that the sea snail produces for its eggs could influence the prosthetic implant of the future, and the shells of the tiny plankton Hildebrand studies could be the template for optical circuitry vastly more efficient than the electric or glass components we use now. The quest to understand nature's designs has taken both researchers into the growing field of biomimicry.



AN INTRICATE ART FORM, AN INTRICATE SCIENCE

The attempt to imitate nature in the form of synthetic products has changed since de Mestral turned his simple observation into a useful innovation. The field of biomimetics has become more sophisticated, and researchers like Rapoport and Hildebrand must first understand the structure–function relationships of an organism.

"We're aiming at finding out something about how this protein gets put together," Shadwick said, referring to the seemingly magical substance that sea snails produce to make the egg capsules. "We're emphasizing the characteristic of self-assembly."

Both studies will require years of work. Hildebrand's inquiry into the amazing structure of the microscopic plankton known as diatoms is a sidelight to his primary focus on diatom molecular biology, nutrient metabolism, and genomics.

Diatoms, about 10 microns (approximately 0.00039 inch) long, exist in countless numbers throughout the oceans of the world, helping to make up the base of the food web. They also are responsible for about one-quarter of the world's total carbon sequestration. In fossilized form, they're the source of diatomaceous earth and are ingredients in all-natural insecticide, concrete, and animal feed.

Diatoms are photosynthetic and make their shells out of silica dissolved in seawater. Derived from the element silicon, silica is the compound used to make glass. In recent years, it has also become the raw material used in the burgeoning field of nanotechnology, which downscales mechanisms to microscopic sizes.

The field's brilliant minds, however, have yet to match the manufacturing capabilities of diatoms. For one thing, a human-made nanostructure is generally made in two dimensions with components added in layers or by the delicate etching of pieces of silica into useable shapes—one laborious piece at a time.

The work of diatoms, however, takes place in three dimensions. They produce their shells

Top, *Graduate student Scott Rapoport uses a vibrating tensometer for dynamic testing of materials.* ***Bottom,*** *A captive whelk lays between 100 and 150 egg capsules per reproductive cycle, each containing some 50 embryos.*

in a seemingly infinite variety of ornate shapes like individual snowflakes, so dazzling that the arrangement of diatoms has been an art form, albeit an obscure one, practiced since Victorian times by very patient people using microscopes and single-hair brushes.

More interesting for Hildebrand's purposes, though, is that diatoms form their intricate, glasslike shells by the millions in mere minutes. This is where the nanotechnology payoff may lie.

"There is a general fabrication ability of diatoms that we can't even approach," he said. "If we wanted to, in the course of a week, we could get them to make over a billion copies of a particular structure for probably less than a dollar per batch."

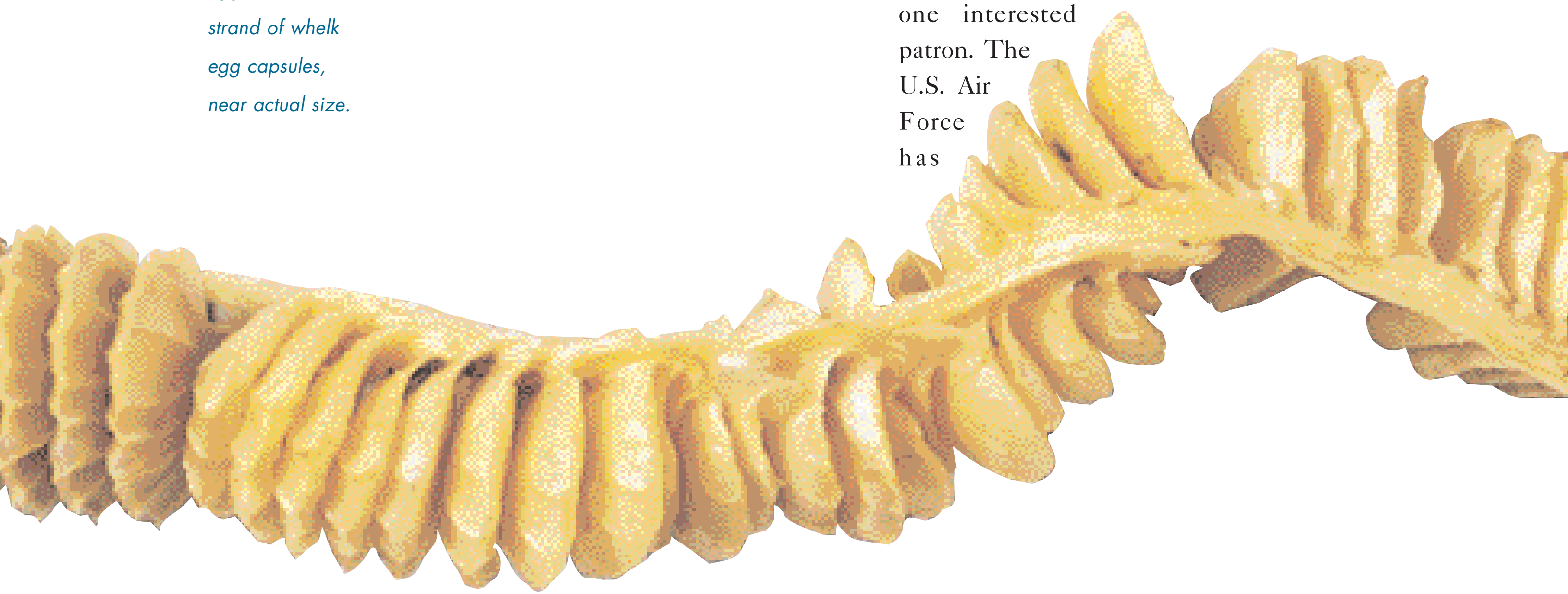
Above, *Rapoport injects a neural extract that causes the whelks to lay eggs.* **Below,** *A strand of whelk egg capsules, near actual size.*

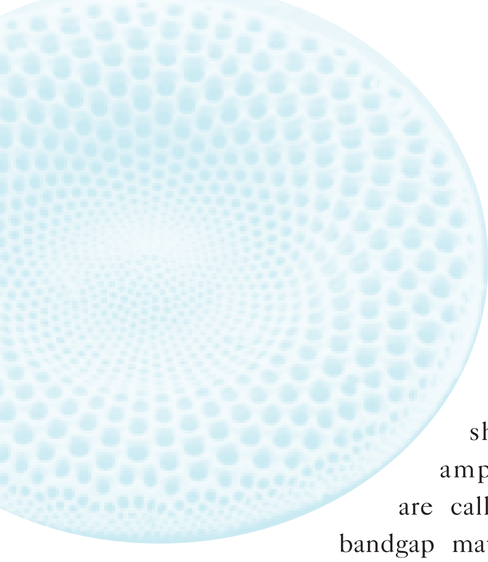
The size of the pores in diatom shells fluctuates with basic environmental changes like the salinity of the seawater. If that size and other traits could be reliably controlled, manufacturers could create new compounds or truly space-age polymers. For instance, the silica shells could house laser dye to create micro-lasers, devices to do the work of common lasers on a much finer scale than is now possible.

In an even more cutting-edge pursuit, other researchers have been able to replace the silica in a diatom shell with other materials such as magnesium.

"By replacing the silica with a metal, you might be able to combine electrical and optical properties in the same device," Hildebrand said.

Currently Hildebrand has one interested patron. The U.S. Air Force has

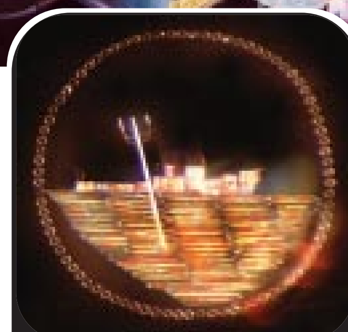




provided some funding for a study of optical properties in diatom shells, an example of what are called photonic bandgap materials. They possess the ability to route light by blocking some wavelengths, and allowing others to pass through their structure. Fiber-optic materials, which transmit information by converting it through pulses of light, are also made of glass but absorb 70 percent of the light. The porous three-dimensional structure of diatoms enables routing of light with only two percent absorption.

The diatom structures are too small to create better optical cable, but they could be ideal for creating ultrasensitive sensors. On a computer circuitry scale, they could prove a boon to computer chip makers looking for more efficient ways to move information across nanometer-sized spaces.

"Although the downsizing of chips by the semiconductor industry has enhanced our information storage and processing capability, there are limits to the amount of information that can be processed using electrons," Hildebrand said. "Light can carry a lot of information, which is why optical circuitry is seen as the major paradigm shift in this technology."

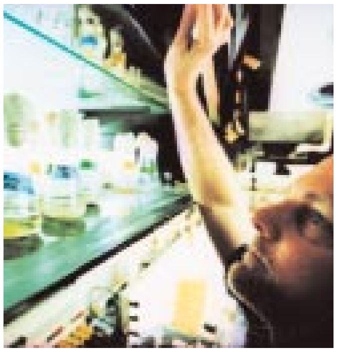


Above, *Hildebrand in the laboratory.* **Right,** *Diatoms as art: Each element of the Scripps Institution of Oceanography logo is a diatom or diatom segment.* **Below right,** *A diatom as seen by electron microscope.*

THE DECONSTRUCTION OF SPECIES

Some biomimicked creations needed fairly simple observations for their genesis. The Eiffel Tower's design is based on the weight-displacing shape of leg bones. The inspiration for the support beams of the glass roof of the Crystal Palace, built for London's Great Exhibition of 1851, was a tropical lily whose 12-foot-wide leaves are ribbed to accommodate their enormous span.

Although de Mestral needed only a magnifying glass to reveal the



secret of the sticky burrs, Rapoport and Hildebrand use more sophisticated tools. Before any synthetic biomimetic products can be made based on sea snails or diatoms, the two researchers must find the genetic code that dictates how these creatures construct the compounds that make them unusual.

Genetic tools for the diatom are rapidly being developed. Researchers have completed sequencing of the entire 24 million base pairs of a diatom genome. Once a genome is known, all of the proteins of that organism can be identified, and subsequent research can determine the function of each protein.

This page,

There are more than 10,000 different species of diatoms living in oceans, lagoons, bays, and freshwater lakes.

With no such genomic guidebook for sea snails, Rapoport has been taking a different approach to learn about the proteins in the egg capsules.

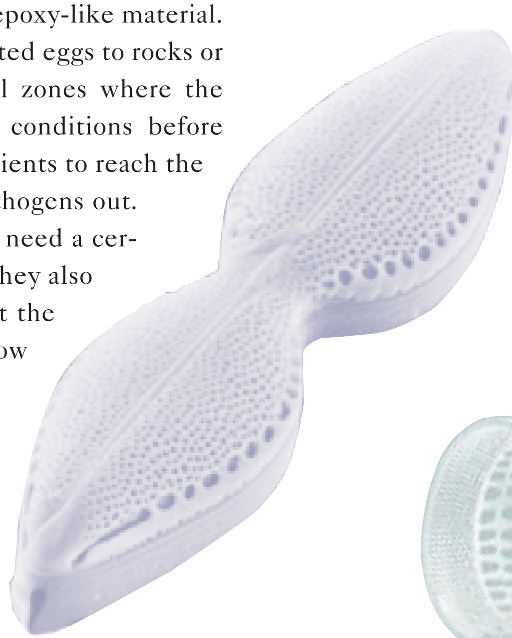
Shadwick first considered the challenge of the capsules a decade ago but did not give Rapoport the project until 1998, when funding became available. The student began his inquiry by first observing the properties of the egg capsules.

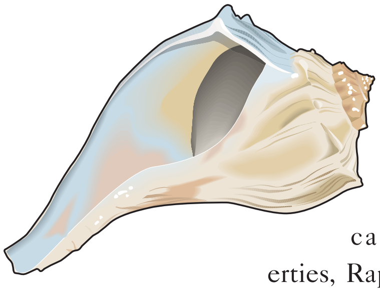
The sea snails that make them, also known as whelks, can be found in most oceans. At the peak of their reproductive cycle between October and December, female whelks release their eggs by laying them inside capsules that look like thick coins. Some whelk species string their eggs together along a common strand so that the finished product looks like a spiraling stack of poker chips. Just before the eggs are laid, a process of particular interest to Rapoport takes place within the whelks' reproductive gland, and the egg capsule transforms into an epoxy-like material.

Some whelk species anchor the encapsulated eggs to rocks or other undersea structures, often in intertidal zones where the embryos must endure months of turbulent conditions before hatching. In that time, the capsules allow nutrients to reach the embryos from the water but keep harmful pathogens out.

Given such an environment, the capsules need a certain amount of toughness and resilience, and they also need to stretch but not retract so quickly that the recoil damages the delicate embryos. Waite, now a professor at the University of California, Santa Barbara, and his son had been fascinated to see that the capsules indeed stretched like rubber bands then returned to their original shape—very slowly.

"This is the adaptive stroke of genius that the egg capsules profit from," Waite said. "The waves are going to come in and beat the heck out of the capsule. You don't want that energy to damage the embryos, and you don't



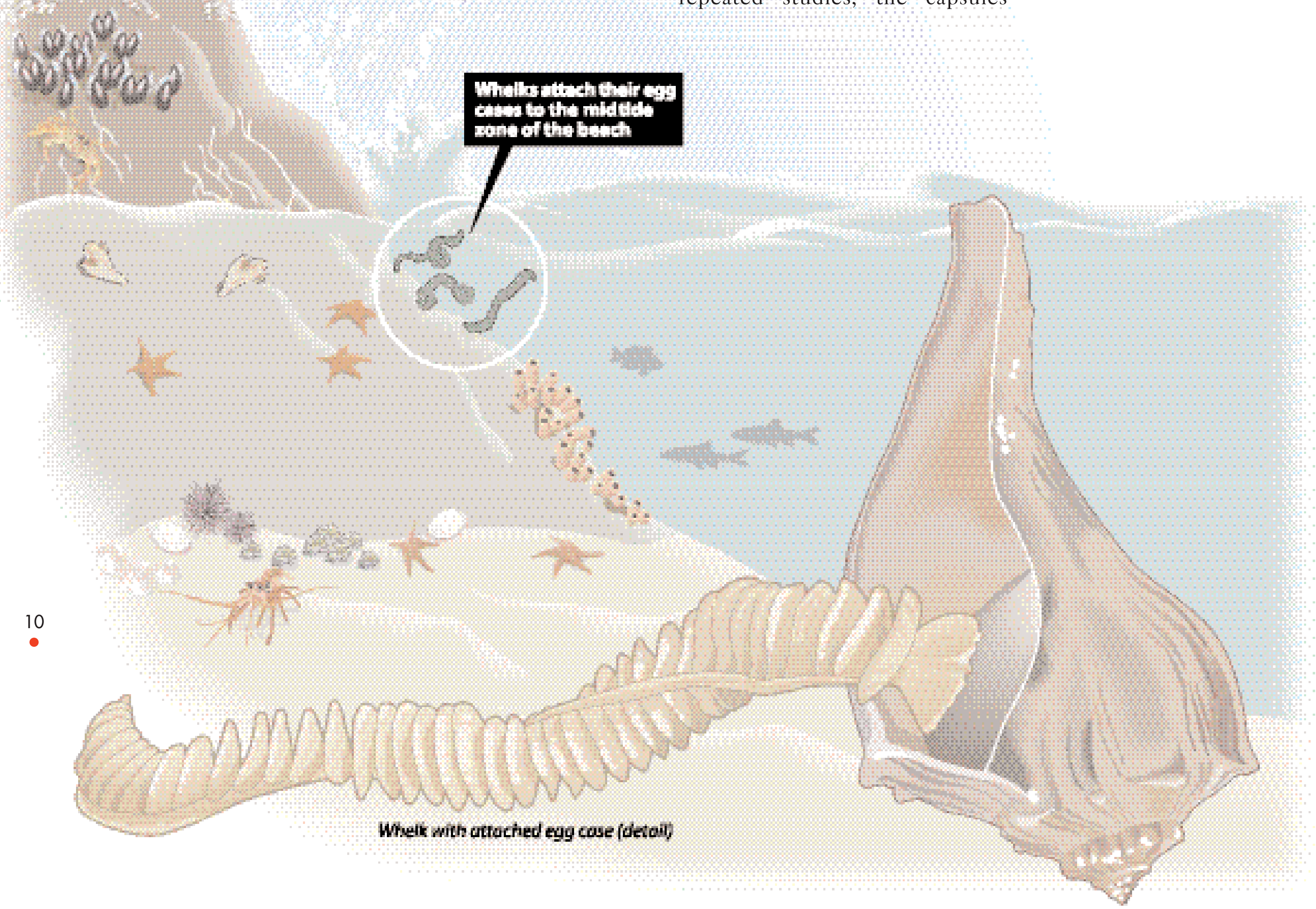


want the elastic energy to slingshot against them."

To determine the egg capsules' various properties, Rapoport put them through a series of stress tests. He measured the mechanical hysteresis of the capsules, the energy that is dissipated as the capsule material returns to its original shape. Think of a rubber band being pulled. There is energy being transferred to the material as it is being stretched. When the rubber band is released, energy is released, though some of it is expressed as frictional heat. That energy track can be plotted as a substance is pulled and then allowed to retract. The capsules, probably as a response to the waves that batter them, have an unusual dual-nature mechanical response. This phase consists of high stiffness that becomes one of rapid energy dissipation as the material gives way under greater stress. These properties are consistent with other shock-absorbing materials.

In the tests, Rapoport used a device called a tensometer, which clamped its "fingers" around slivers of capsule material. The machine pulled on the pieces in short bursts and relaxed in rapid fashion, dozens of times in a minute, "jiggling them at different frequencies," as Rapoport put it. In repeated studies, the capsules

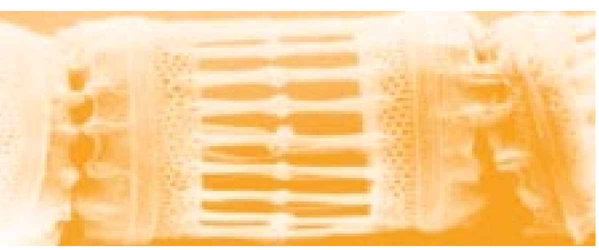
Below, *A whelk egg's strength can be linked to adapting to its rugged environment along the coastline. Researchers hope to duplicate this durability in the laboratory for a variety of uses.*

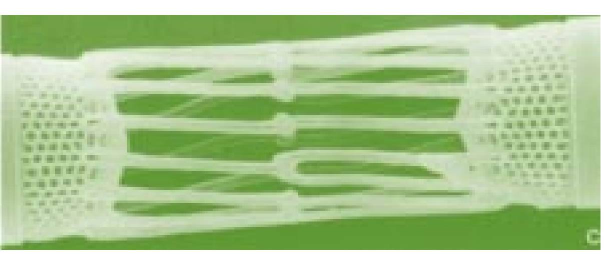


endured long-term cycles of stress. They showed a rare ability to return to their initial state after being stretched beyond the point of apparent failure, the point at which some materials become permanently deformed, like a metal spring pulled irrevocably out of shape.

Rapoport found that protein makes up more than 90 percent of the egg capsules and that the protein is probably related to those that perform similar functions in the human body. In your skin, the protein collagen limits the amount it can be stretched while elastin returns your skin to its original shape.

The whelk essentially has a heavy-duty version of those human proteins. The strength of its proteins has led Shadwick to consider its use as a durable substitute for damaged or worn human ligaments or tendons. Future biomimics could imitate the structure of whelk proteins as the basis for structures that have special durability and elasticity requirements.





Now that the mechanical properties of the whelk capsule are known, the next step is to study its composition. The task is difficult because the insoluble egg capsule cannot be broken down into its individual components; it appears to be irrevocably joined by cross-linkage, a biochemical binding process.

Rapoport is trying to identify the capsules' ingredients by seeing what is present in the snail early in the reproductive process, before the compounds are integrated into the egg case. Figuring out how they come together, though, could mean years of further research.

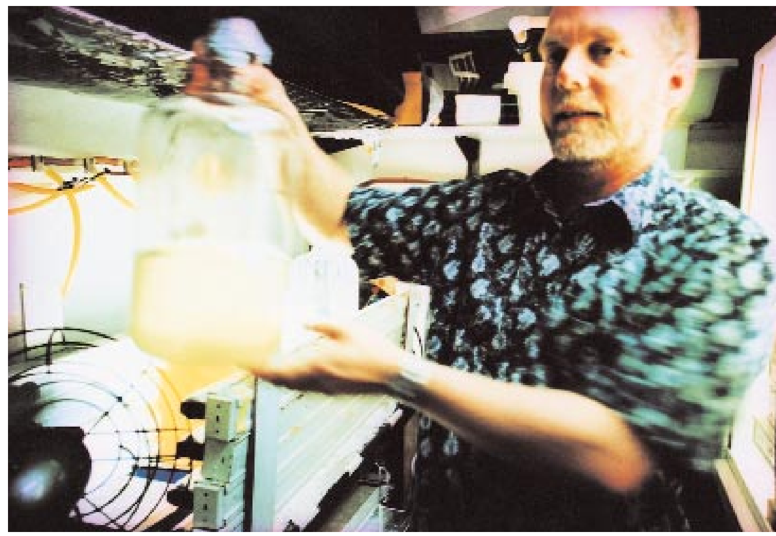
"We know that something changes, but we have no idea what," Shadwick said. "If there's something added, if there's some magic chemical, we don't have any evidence of that. We've got a lot of information, but we don't have the whole picture."

MICRO TO MACRO

Rapoport's immediate goal is to add some new information to the database of known proteins and their functions, even if their relationship to each other in whelk capsules isn't known.

"The chief value [of the research] is in understanding how molecular-scale structure and arrangement influence macroscale mechanical behavior of polymeric material," Rapoport said. "For biomimicry, if you can figure out the properties from pretty standard components, then when you're making materials, this information will help you design for a certain mechanical property."

Hildebrand believes it will be awhile before the potential of diatoms as biomimetic muses is realized. He notes that the transistor languished as an invention without an application for some 20 years before making itself indispensable as the basis of computer chips and radio receivers.



Above, *Diatoms could be produced by the billions for "probably less than a dollar per batch."*

"We're going to come up with interesting little things right now, but it's going to take some time to figure out a way to use them," Hildebrand said. "We don't know how it's going to pan out, but everyone's sure it's going to be beneficial."