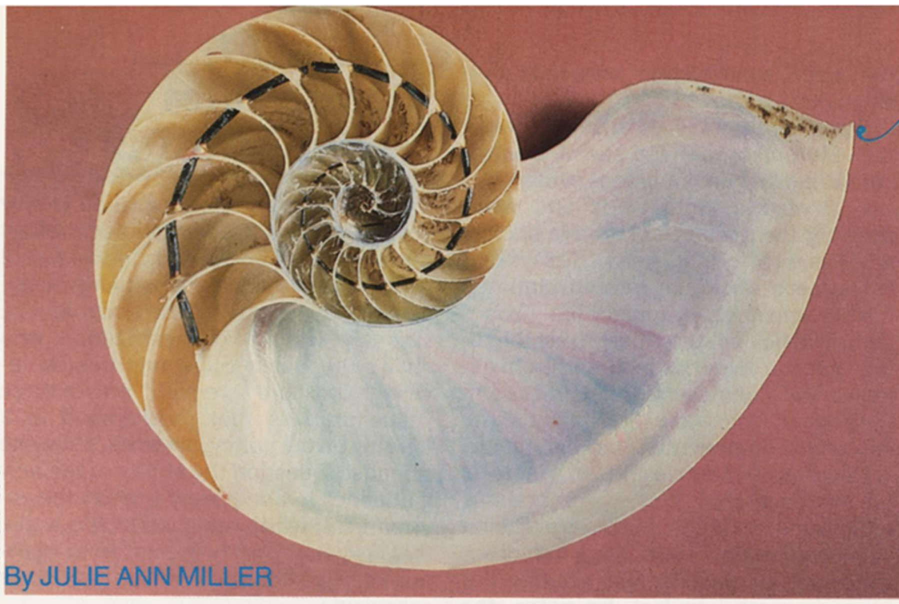


Photos: Saunders

Artful Adapter

Recent observations of the chambered nautilus, often considered an evolutionary dead-end, indicate that it is instead a thriving, diversified modern genus

By JULIE ANN MILLER

The delicate beauty of the nautilus, with its pearly shell and intricate chambers, was described as early as the time of Aristotle. This shell has long been in use around the world for decorative purposes. Because the modern shell closely resembles fossils of ancestors living millions of years ago, scientists have called nautilus a living fossil. But biologists and paleontologists are now discovering that the modern beast inhabiting the spiral shell is a highly specialized animal that, rather than being at an evolutionary standstill, is evolving at a rate faster than that of many other modern animals.

While nautilus shells are commonly found in the Indo-Pacific area, the living animal has been elusive. Only within the last decade have scientists been able to maintain in captivity this deep-sea cephalopod, a relative of the octopus and squid.

With live nautiluses available in the laboratory, biologists are beginning to investigate puzzling aspects of their physiology and development. Last year, researchers took their first look at a nautilus embryo — in an egg laid by a captive female. And in the natural habitat, time-lapse photography deep in the ocean is documenting the nautilus's lifestyle.

"Few organisms have been as well known to the layman but as poorly known to science as the chambered nautilus," said paleontologist W. Bruce Saunders recently in Philadelphia at the annual meeting of the American Association for the Advancement of Science. At the meeting a group of biologists and paleontologists presented what they believe to be the first multidisciplinary symposium focused on the nautilus.

Although today only five or six species of nautilus are known, fossils indicate that there were once more than 17,000 species inhabiting the seas. These "nautiloids," the earliest cephalopods to appear in the fossil record, are thought to be the first organisms with jaws and consequently to be among the first predators, says Saunders, of Bryn Mawr (Pa.) College. Only one nautiloid group survived the massive extinctions that also destroyed the dinosaurs.

"Paleontologically, having access to [the modern] nautilus is somewhat like having a single living dinosaur," Saunders says.

Is this underwater dinosaur in mint condition, or has it been altered by the millions of years?

"Until a few years ago," Saunders says, "I shared the general view that nautilus is a relic: a last-legs holdover, essentially doomed by its antiquated design and inability to compete with the faster, more agile and intelligent squids and fishes.

"But recent work with this fascinating animal indicates that it shows exceptional — perhaps unique — adaptations. The picture now emerging is that nautilus is secure in its role, and successful enough to be a common component of Indo-Pacific island reef complexes. Work in progress indicates that differentiation has occured between isolated populations of the most common species, *Nautilus pompilius,* raising the possibility that this ancient lineage may once again be on the point of diversifying."

Twenty-five million years ago, nautiloids occurred in seas around the world, but now they are restricted to a region from the Philippines south through Indonesia to Australia and eastward to the Fiji Islands. In some sites they seem sparse. But in other places they are quite abundant. "We find some every time we put down a trap," Saunders says.

He and his colleagues have captured, labeled and released approximately 3,000 nautilus specimens. Some individuals have been recaptured as many as five times and some as long as four years after release.

From these studies the scientists have learned that a nautilus can travel as far as 150 kilometers per year. The adults grow slowly, adding only one chamber annually. Although the natural life span is still uncertain, individuals survive at least four years after maturity, which they reach at an age of about 10 years.

In the well-populated areas, 30 to 60 nautiluses will enter a baited trap over a three-day period. Using a camera programmed to take a picture in the deep water every 15 to 30 minutes, the scientists have learned that the nautilus shares its preferred territory — at depths of 150 to 300 meters — with eels, crabs and shrimp.

The nautilus had been thought to be nocturnal. Indeed, in shallow water, it is active only at night. But at greater depths, the photos show, the nautilus is also active during the day. Saunders suggests that the fast-moving, bony fish inhabiting the shallow waters have forced the nautilus into a nocturnal niche. Experiments using a sonic transmitter attached to a specimen show that some nautiluses spend the days in shallow water and the nights at greater depths.

"We think [the nautilus] originally evolved as a shallow-water organism," says geologist Peter Ward of the University of Washington in Seattle, who has studied the nautilus in both living and fossil forms worldwide. "The move to greater depths extracts a price both in growth and in reproductive strategy."

Several factors limit the depth of the nautilus habitat. The most obvious is that its shell will be crushed by the water pressure at about 800 feet. But the creature is seldom found below 500 feet. Ward suggests that this limit is due to the animal's unique buoyancy mechanism.

The nautilus uses the chambers of its shell to suspend itself at a suitable depth. If it were to float to the ocean surface, it would likely die from either the increased temperature or an attack by fish.

Right: Immature and mature Nautilus belauensis. *The animal takes 11 to 14 years to mature and may live 4 or more years beyond that. Facing page: Shell cross section.*

Eric Denton of England's Marine Biological Association was the first to describe the nautilus buoyancy mechanism. As the chambers of the shell form, they enclose seawater, most of which gets pumped out. But, Denton says, the animal can adjust the amount of liquid in the outermost chambers to change its buoyancy. It is the same mechanism as bailing out a boat to make it ride higher in the water.

The buoyancy mechanism requires feedback as the animal changes depth and also weight. In laboratory experiments, Ward has found a nautilus can adjust its buoyancy to compensate for a gain or loss of 5 grams. This takes about 80 hours. Ward says an animal naturally may lose weight when its shell is chipped, from either an attack or a collision with a hard object. The nautilus naturally gains weight during a heavy feeding.

The greater its depth, the more difficulty the nautilus has pumping seawater out of its chambers against the external water pressure. Below 500 feet, it may not be able to adequately control its buoyancy.

The difficulty of emptying its chambers of seawater at great depths may also limit the nautilus's growth rate. By looking at X-rays of nautilus specimens, Ward has determined characteristics of shell growth.

A thin partition first seals off a compartment, then is gradually thickened, Ward reports. When the partition reaches half its final thickness, seawater begins to be drawn into the central tube. The loss of the liquid creates a near-vacuum in the compartment.

When only about half the seawater has been drained from a compartment, the nautilus begins forming its next chamber, Ward was surprised to find. The larger the animal, the longer it takes to form a compartment. The calcium for making new chambers comes from a diet of crabs — eaten shell and all — and the molts of various animals.

More than its buoyancy mechanism distinguishes the nautilus from its living relatives, none of which have an external shell. Compared with the other cephalopods — squid, octopus and cuttlefish — it is slow-moving, slow-growing and dim-witted, says Martin J. Wells of Cambridge University in England.

The metabolic rate of a nautilus at rest is about half that of an octopus and one-third that of a squid. On a graph depicting the ratio of brain weight to body weight in various animals, the squid is in the upper ranges, between mammals and fish. The nautilus falls far below, beneath fish and reptiles.

The nautilus also has a reproductive strategy unique among the cephalopods. "Nautilus is wildly different," Wells says. The other cephalopods grow rapidly, reach sexual maturity after a year or two, breed once to produce numerous offspring, then die. Wells calls this lifestyle "big bang reproduction." In contrast, the nautilus matures slowly and breeds for at least several years after reaching sexual maturity.

Some scientists attribute the nautilus's slow growth to its deep habitat and need to pump out chambers. Wells suggests that food shortages in nature also may play a role, because a nautilus in captivity grows more rapidly. But he proposes that the major factor in the animal's reproductive strategy is its reliance on scavenging for food.

Scavenging in the ocean requires a sophisticated set of sensory and motor abilities. The nautilus detects much of its food by smelling — or perhaps one should say tasting — chemicals in the current coming from a carcass. Then it must determine which direction is upstream and swim against the current.

Scavenging activity requires a nervous system capable of integrating chemical, visual and tactile information. The nautilus must also have a jet sufficiently powerful to propel it upstream. Jet propulsion is most effective in large animals, Wells says.

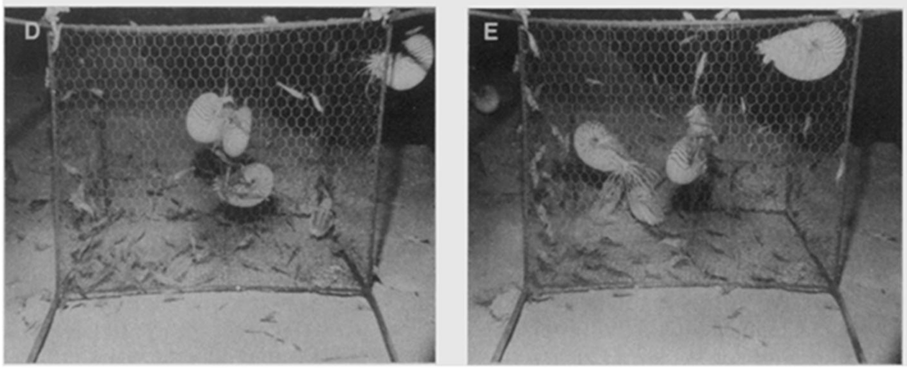
Wells proposes that the scavenging lifestyle requires a newly hatched nautilus to be relatively large and mature, so that it can be a fully operational scavenger. "As soon as the baby hatches, it has to do something complicated," he says. Consequently, the nautilus must lay large eggs, and rather few of them.

"This is the mammalian strategy: Invest much in each egg," Wells says. "That's risky unless you keep at it over several breeding seasons."

The relatively large nautilus hatchling appears to be a recent innovation in evolution. "The modern nautilus lays larger eggs than any nautilus in the past," Wells says.

By looking at modern or fossil nautilus shells, scientists can determine the size

These two specimens of N. belauensis, *captured at a depth of 300 meters, were tagged and released three times in a study of nautilus movement, growth and longevity.*



At a depth of 284 meters, a camera/strobe set to fire every 15 minutes reveals the night life of the nautilus. Using chemosensory cells lining its tentacles, the nautilus detects a tuna bait – hence the "smelling" posture of the animal swimming backward until it bumps into the trap in photo B. Having localized the scent, it swims forward, groping with tentacles (C). Once the bait is gone, the animals begin leaving (D,E). Trap is 3 feet across; nautiluses are surrounded by shrimp. Photos were taken off Palau, in the West Caroline Islands.

at which the animal hatched by a change in shell texture from smooth to rough. Ancestors of the modern nautilus hatched as much smaller animals, Wells reports.

This observation also indicates that the modern nautilus lifestyle is a recent development. The young of ancestral nautiloids, Wells says, "could not possibly have adopted the [modern] nautilus lifestyle."

"Nautilus alone, exploiting a specialist environment, developing special behavior and a special sort of life history, survived until the present day," he says. "[It is] a living fossil in terms of its shell, a highly specialized modern animal in terms of its physiology and lifestyle."

Scientists have just become able to study development of nautilus before the hatchling stage. At the University of Hawaii in Honolulu, John Arnold reports that he and his colleagues have obtained seven live embryos, including two species, from eggs laid by captive females. The scientists also have examined shells of other embryos that died.

The embryonic nautilus shell is constructed from a mosaic of bits of shell laid down in irregular circles, Arnold reports. He also has found that the yolk sac has contractile musculature, and the embryonic heart pumps blood through an extraembryonic circulatory system not seen in other cephalopods.

Arnold is particularly interested in the embryonic nervous system. "We want to follow neuroembryology to give insight into the development and evolution of an alternative form of [cephalopod] intelligence."

One aspect of nautilus intelligence, its visual system, is being examined by William R. A. Muntz of Monash University in Australia. The nautilus eye resembles a pinhole camera; there is no lens, but simply a pupil open to the sea.

Muntz has tested nautilus vision by putting an animal in a rotating drum lined with a pattern of stripes. He allows the nautilus to follow the stripes as the drum turns. By replacing the lining with patterns of progressively narrower stripes, he can measure the animal's visual acuity.

As expected from the simplicity of the eye, the acuity is poor. Muntz calculates that the nautilus can distinguish at 9 inches an object that a person with good vision could see at 150 meters.

Using T-shaped and Y-shaped mazes, Muntz has measured the nautilus's sensitivity to light. The animals generally will move from a darker to a lighter area, so he can tell when they can distinguish different light levels. Although its sensitivity is duller than that of many other animals, it appears to be adequate. "Nautilus can see something right down to the bottom of its [depth] range in bright [sun] light," Muntz says.

In what Muntz says is the only behavioral study of spectral sensitivity in a deep-sea animal, he found that the nautilus seems to have only one light-absorbing pigment, which is most sensitive to blue light.

For what does the nautilus use its vision? Muntz proposes that, in addition to sensing and orienting itself in ocean currents, the nautilus may directly look for prey. For example, it may perceive bioluminescent shrimp accumulating around a carcass on the seafloor.

As to whether the nautilus is a living fossil, the ultimate answer is likely to come from genetic studies. "We have begun using molecular genetics to get at the genetic underpinning of this allegedly arrested evolutionary change," reports David Woodruff of the University of California in San Diego.

As other scientists have captured, marked and released nautiluses, they have snipped small tissue samples from the tips of the tentacles. Woodruff has used this material to look for differences in 21 genes. If the genus *Nautilus* were no longer evolving, he would expect to find little variety in the genes.

"The most common species, *N. pompilius*, is extraordinarily variable," Woodruff reports. It is far more variable than the human species, he says. In fact, his data suggest that an *N. pompilius* population found in the Fiji Islands may need to be classified as a separate species.

Some of the other nautilus species are impressively variable, but those in isolated areas have less variation. Using the average rates of genetic change determined for other animals, Woodruff suggests that today's nautilus species diverged from each other only 1 million to 5 million years ago.

"We're at the early stages of what appears to be a new radiation [of species]," he says. "This is the ongoing evolution of a new group of shelled cephalopods. There's life in the old line yet." □