Shape of Life

Echinoderms: Give Me Five
An Ultimate Animal

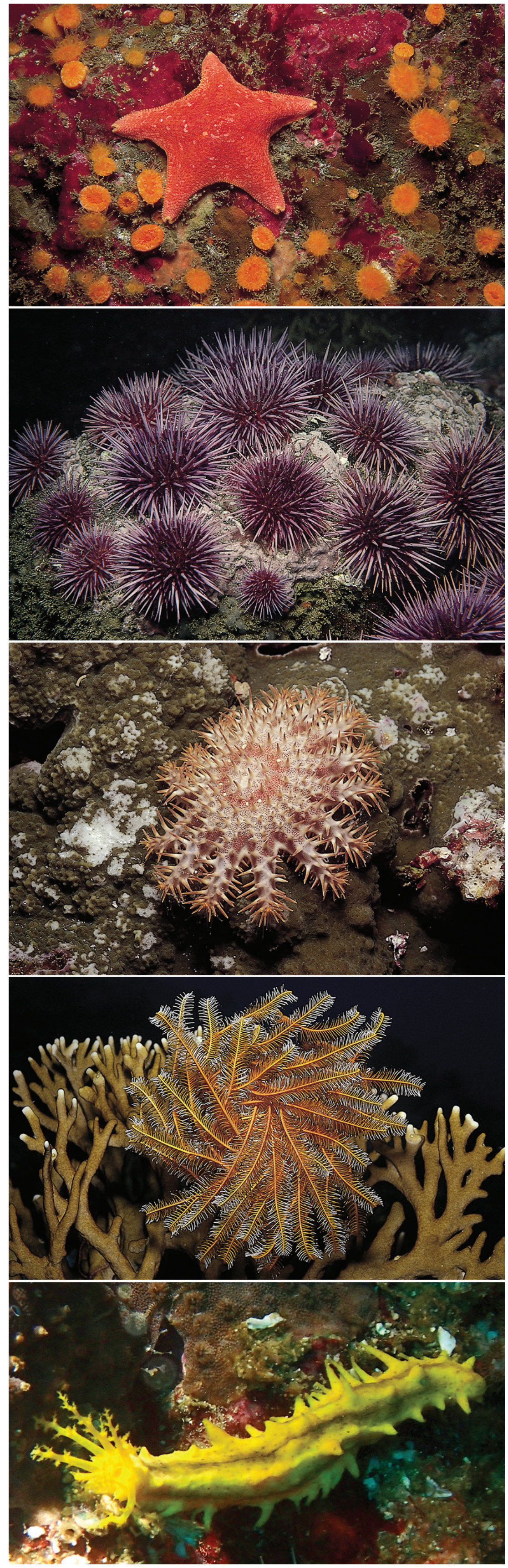
An insightful seventeenth-century Frenchman could have been talking about echinoderms when he said, 'It is well to comprehend clearly that there are some things which are absolutely incomprehensible.' So might a twentieth-century marine biologist when he said, 'If there are animals from another planet already here, they're probably starfish.'

PEARSE AND BUCHSBAUM, *LIVING INVERTEBRATES*

The evolution of animal life has not followed the rules of good theater by revealing its themes, characters and conflicts in clear stages, leading to an inevitable climax. If it had, the story of body plans would have proceeded directly from sponges through cnidarians and flatworms to the explosion of annelids, arthropods, molluscs, and chordates, stopping there with a fanfare of trumpets, drums and applause. After all, that story line produced heads, brains, eyes, intricate systems for active living, and a variety of bilateral shapes that met the heroic task of surviving for hundreds of millions of years. But at the end of what should have been the final act in the drama of animal complexity, the echinoderms waltzed in from the wings, took center stage and said, “No. Hold on. That’s not the only way to evolve. Let’s try it again.”

Even if you accept the notion that nature has no obligation to make sense, echinoderms are enigmas that evolved like no other animals on earth. Their curtain went up over half-a-billion years ago, along with those of all the other basic blueprints for building an animal, but they tell an entirely different evolutionary story. After the appearance of the first ancestor of multi-cellular animal life, in the form of a creature we call a sponge, most of its descendents set off in the direction of bilateral bodies, heads, central nervous systems, and brains. They adapted complex tissue, organs, and sensory systems to live in the sea, on land, and in the air. This powerful assembly of body components made great sense for hunting, surviving the attacks of other animals, and continuing to adapt to constantly changing environmental conditions.

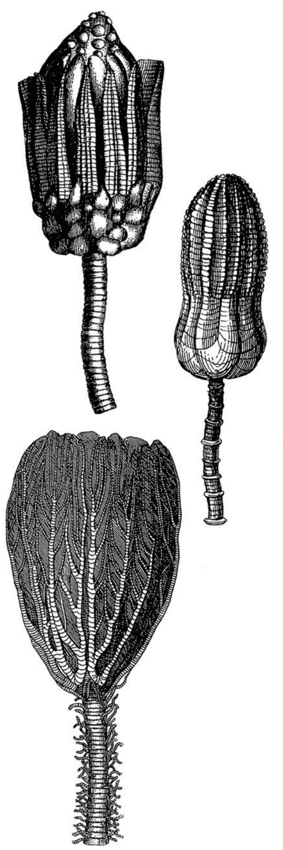
Those streams of animals rising from the Animal Eve branched into each of the thirty-five or so phyla, including the eight to which ninety-five percent of all animals belong. From those major turning points in the river of life grew the billion or so species that have called the earth home ever since. At some point, though, one of those eight basic ways of being an animal diverged so radically it hardly seems to belong to the same world of the others. These are the echinoderms. Their name means ‘spiny-skinned,’ but their unique portrayal of life is about much more than that.



Top to bottom: Bat star, purple urchin, crown of thorns star, crinoid, sea cucumber

In a fast-paced world, the echinoderms chose to live in the slow lane. Their bodies seem to be little more than skeleton and water. They don't use large muscles working on large body parts like other animals. Instead they move on hundreds of tiny, water-filled tube feet operated by a hydraulic system that can't produce high-speed movement. Their skeleton is made of tiny calcium carbonate plates, and their five-sided bodies interact with the world equally from all directions, without a head to lead the way. This low-energy body doesn't require lots of fuel. How did such an alternative life style get created and sustained by the evolutionary forces that drove most of the animals of the Cambrian towards a bilateral approach to life?

Five-part Success



Fossil crinoids

Echinoderms have such an unusual body plan, you might think that it was just an experiment that didn't go anywhere, but that's quite wrong.

Andrew Smith, Paleontologist

The first sure evidence we have of the presence of these non-conforming interlopers comes from fossils that formed in the early Cambrian, about 535 million years ago, and they don't look much like their modern descendents. The primitive echinoderms lived on the sea floor and moved slowly, if at all. Some of the traits of their race are present in these early fossils, including the calcite skeleton and the water vascular system powering its tube feet for locomotion. Yet it appears that evolutionary experimentation was taking place with body symmetry, for there are three-sided and four-sided bodies, and even bilateral forms. It could be that the earliest stages of the echinoderm way of life were bilateral, but for some reason that approach didn't work well within the constraints of their other, already established body parts..

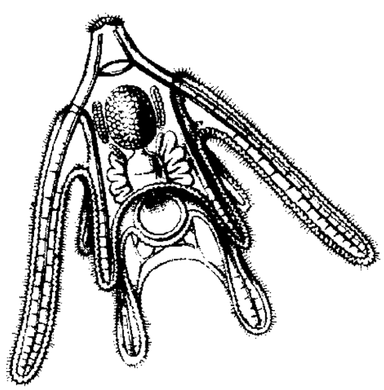
The five-sided, or radially pentamerous, body now sported by most modern echinoderms doesn't show up until a few million years later, in a group of extremely weird creatures called crinoids. These characters, easily mistaken for plants, were clearly five-sided forms splaying open five arms to catch tiny food drifting by in the water. Five-sided symmetry was a good strategy for living a filter-feeding life attached to the bottom. If you're stuck on the sea floor in one place, why not meet the environment equally from all directions? This way of life was extraordinarily successful. Some forms even got themselves off the bottom and into better position for filter-feeding by growing stalks., Many of them became giants rising as high as 70 feet off the sea floor, not by swimming but more like the first human aviators who rode as look-outs in tethered balloons above battle fields. With bilateral symmetry catching on all around them, with fronts and backs and heads and tails proliferating, with brains, eyes and guts beginning to evolve, the early bilateral echinoderms just might have been outdone by other bilateral animals. So they began doing things differently.

Crinoid

Since they abandoned their early bilateral experiments, echinoderms have been on a kind of evolutionary side trip. Try to imagine coming up with a new way to build a land vehicle that is elementally different than the cars, trucks, and SUVs clogging today's highways. To achieve the same magnitude of divergence as echinoderms managed from the basic architecture of all other animals, you would have to dispense with wheels, hoods, trunks, and most of the components of engines. You would have to abandon the concepts that a vehicle moves in forward or reverse gear, that it is propelled by a single power source, and even that a driver is required to drive it. You would have to abandon all of the highways, bridges, tunnels, and speed limits that co-evolved with the design of cars, trucks and SUVs. Whatever you come up with in a radically new vehicle will require an entirely different environment for moving around. The evolution of vehicles for common use on highways has already produced a workable result, so yours would be very, very different and not at all intuitive or logical. And perhaps not even possible.

It is worth noting that the spiny-skinned echinoderm revolutionaries do possess the basic traits of animalness: they are made of many cells doing specialized work but interacting to produce a functioning whole; they are the product of the fertilization of a large egg by a smaller sperm; and from this single cell they transform themselves in a highly organized way into an adult body. The regulatory Hox genes governing that transformation are amazingly similar in all bilateral animals, so there must have been a first ancestral bilateral form that passed those genes to all its progeny during the Cambrian explosion of diversity.

But what about the echinoderms? As it turns out, they also have some of those same Hox genes, but in their bodies they direct the formation of an entirely different shape. Modern echinoderms still produce larvae that are bilaterally symmetrical, more evidence that leads some investigators to conclude that they must have risen from an early bilateral ancestor.



Bilateral echinoderm larva

Being different, however, seems to have worked out just fine for the echinoderms. About 6,500 named species of their phylum still inhabit Planet Earth, not a giant tribe compared to the 750,000 kinds of arthropods or 70,000 molluscs, but they are spread throughout all the world's oceans. Echinoderms are almost exclusively bottom-dwellers, although their larvae spend some time drifting in the water column before abandoning that uncertain lifestyle for the security of adulthood on the sea floor.

Five major adaptations of the echinoderm body plan exist today: They are sea stars; sea urchins (and their close cousins, sand dollars); brittle stars and basket stars; sea cucumbers, which constitute the largest biomass on the deep sea bottom; crinoids, which include feather stars and sea lilies. Recently, in 1986, scientists discovered a new class of echinoderms, the sea daisies, which are tiny organisms that live on wood in the deep sea.

You can group animals any way you want to -- eyes, or no eyes; legs or no legs; or by color, or aroma or whatever. But if you are interested in defining the relationships of animals within groups through time, a system based on inherited anatomical characteristics works best and we've been using it since the seventeenth century when the Swedish scientist Linnaeus laid it out.

Since echinoderms emerged about 535million years ago, at least fourteen major adaptations, or classes, of that body plan have risen and died off, in addition to the six classes currently alive. These were huge groups of related animals within which diverse families, genera, and species evolved, and then vanished. Many other classes of animals in other phyla have also gone extinct, but never so many in proportion to the number of echinoderms that survived into the present. The expression of so many extinct classes within one phylum appearing, thriving, and becoming extinct is a microcosmic representation of the evolutionary vigor that went into creating the separate phyla of animals, but with an entirely different twist.

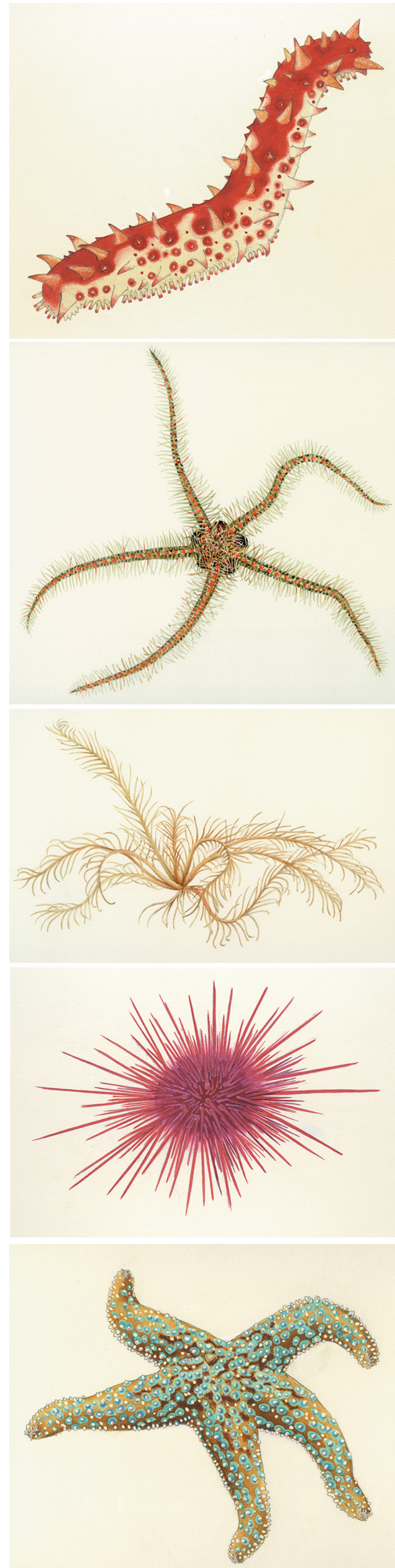
Looking Closely at Echinoderms

> *They are exciting. They are wonderful. It takes some time and some patience to understand them, but the more you look, the neater they get. You really have to watch, they really don't give away their secrets easily.*
>
> Gail Kaaiiali, Biologist

Just about everyone has seen an echinoderm, probably one of those exotic, colorful creatures in a tide pool, on a dock piling, or in an aquarium. They're so obviously evocative of celestial objects that we have named them sea stars (Class Asteroidea.) Really, a star in the night sky is a ball of fire like our sun, but when we look at it from afar it seems to radiate arms of light. Somewhere along the line, perhaps because it's easy to draw, we came up with the five-pointed star as an icon. People used to refer to sea stars as starfish (and some still do) but they are emphatically not fish.

Imagine picking up one of those sea stars, or recall your first real and daring encounter with so strange a creature in an aquarium touch tank. When you pick up the sea star, you notice that it quickly becomes rigid in your hands, a hardened star. Just moments ago, it was flowing like rubber over the rocks in the tank. When threatened, the sea star has the ability to freeze itself and remain so for a long time by changing the physical state of the collagen connecting the tiny plates of its skeleton, thus preventing movement between the plates.

Look at the animal in your hand. Like most adult sea stars, its arms radiate in multiples of five from a central hub. This rule of five can be broken, though, so you might see sea stars with anywhere from four to fifty arms. One giant, Pycnopodia, has as many as twenty arms and grows to twice



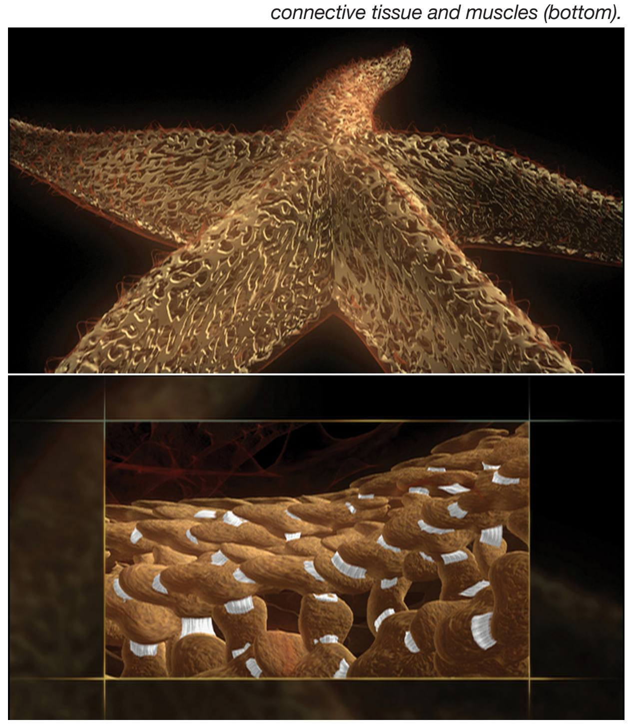
The 5 echinoderm classes: sea cucumber, brittle star, crinoid, sea urchin and sea star. Drawings by Ann Caudle.

the diameter of a manhole cover. Other echinoderms also follow the rule of five. The body of a sea urchin is like an origami sea star, with its arms folded toward the tips of each other to form a ball, but you can still see the five distinct radials, just as you can in its close relative, the sand dollar. A sea cucumber looks very little like a star and more like a cucumber, but it really is made of five distinct sections organized into an elongated tube, an adaptation to a bilateral way of life without losing the rule of five. And if you look closely at crinoids and sea daisies, you'll see their obedience to five-part radial symmetry as well.

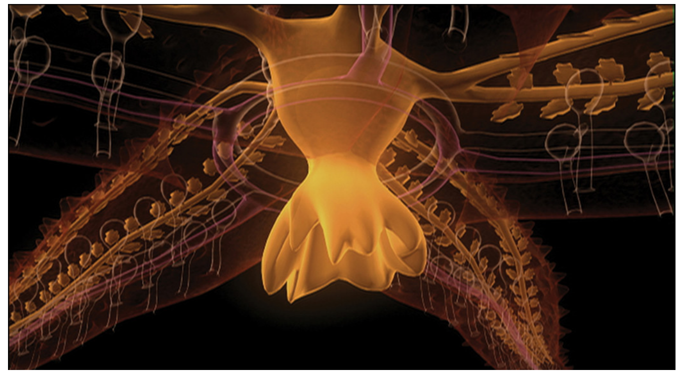
Sea star, urchin and sea cucumber share the same body plan (left).

A sea star has no head or tail, front or rear, but most do have a top and bottom. Feel the sea star with your fingers, and sense its textures and contours. Kind of rough and pebbly, right? Many sea stars, and especially sea urchins, use spines as part of their defense armament, which can nick you, sometimes very painfully. But your sea star, let's say a common tide pool character known as Pisaster, is harmless to a big, intelligent, bipedal carnivore like yourself. The top surface of its body is covered by a thin skin over an internal skeleton of moveable and fixed calcium carbonate plates arranged in a specific pattern, depending on the species. This internal skeleton is unique, and no other animal has anything quite like it to keep itself together and give it shape. The plates are held together by tough connective tissue and small muscles that allow it to flex around rocks, pilings and crannies like an alien ballerina when it isn't frozen in your hand. The plates of a

A sea star's skeleton (top) is held together by connective tissue and muscles (bottom).



sea star skeleton are more like our bones than the hard armor of arthropods or the shells of molluscs, because they grow inside active, living cells. And the skin, too, is a living epidermis, which can extract oxygen and dissolved nutrients from the water.

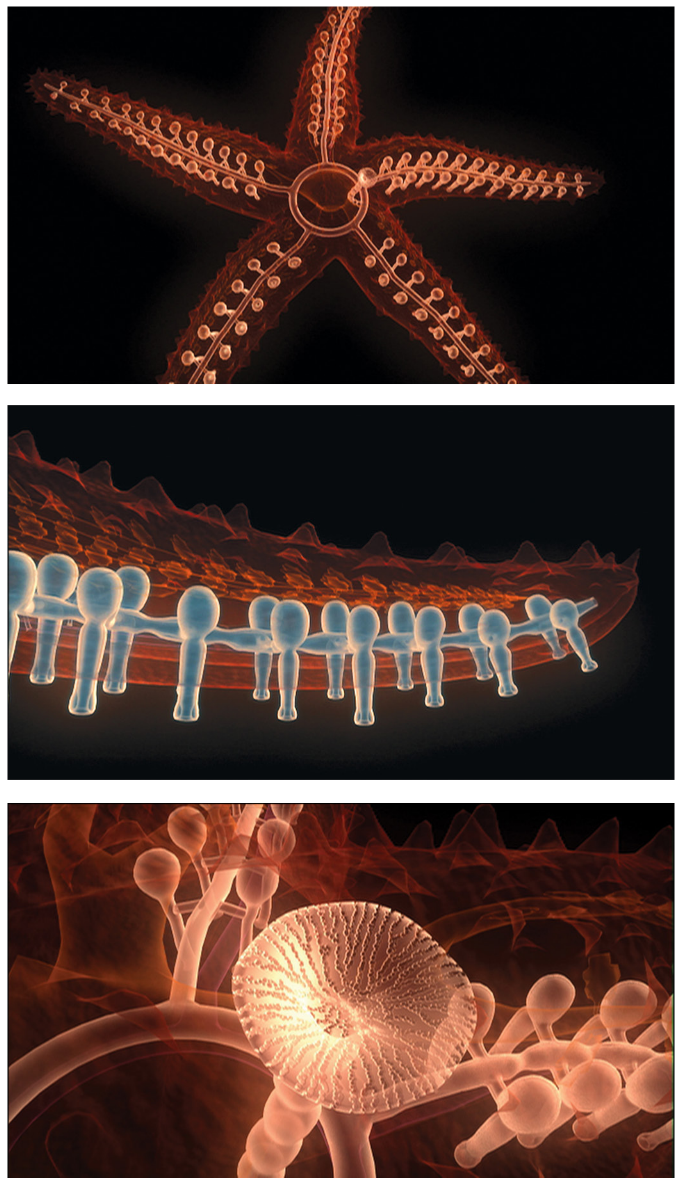


A sea star's stomach extending from mouth.

Now turn your sea star over. Like all animals, an echinoderm has to eat to live. See that opening in the middle? That's its mouth. An echinoderm's digestive system is quite simple. Beginning with that mouth on the bottom side and ending with an anus on the top, it is basically a stomach with pouches for digestion. There is also a simple, though somewhat ineffective, circulatory system in which a clear fluid moves through the body in five directions.

To eat, echinoderms hunt, graze on plants and organic debris, scavenge on the bodies of dead animals, or simply absorb nutrients through their skin from the sea. That sea star from the touch tank is a ferocious, slow motion predator when it comes to hunting down and eating mussels that can't move at all and so are at the top of the star's menu. The sea star senses the mussel with receptors at the tips of its arms, moves to cover it, and clamps down with some of its tube feet. Then it slips part of its stomach through a crack between the shells of the doomed mollusc, liquefies the meat, and settles down to digest its meal.

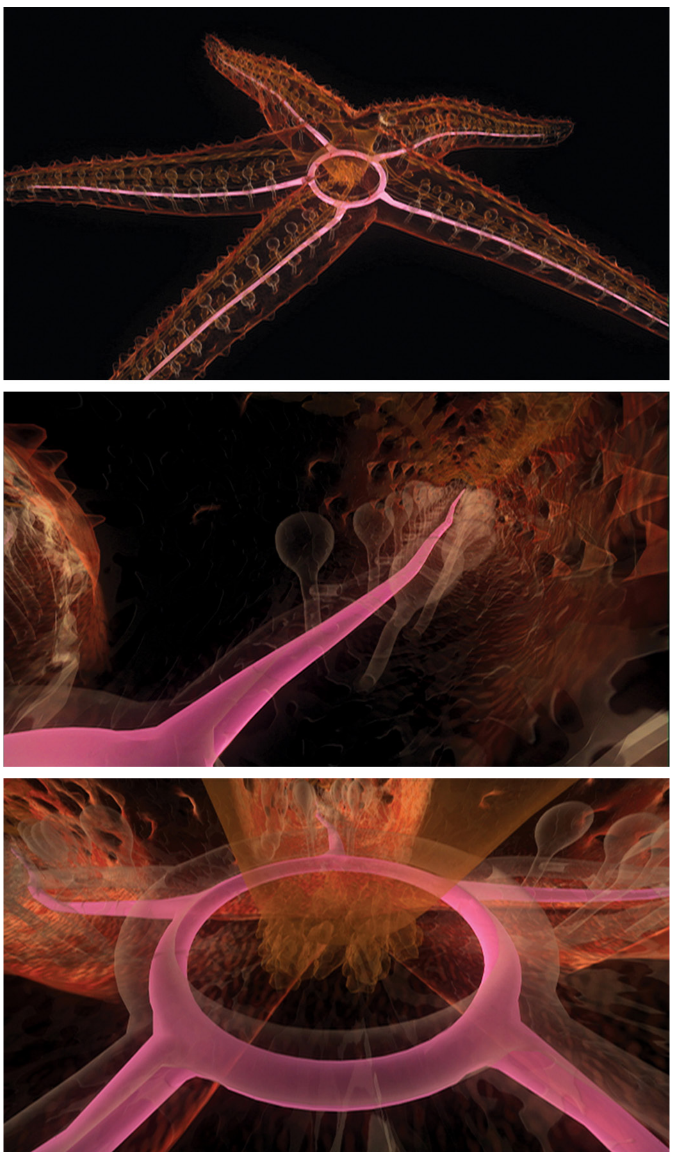
Are you still looking at the underside of the sea star? That's the really creepy part of a sea star, figuratively and literally. You are looking at the marvelous, totally unique echinoderm hydraulic system for getting around. Tube feet. Once you get over the heebie-jeebies from seeing what appears to be a wriggling infestation of worms, look more closely and you can see an array of tubes that together are highly coordinated, very efficient, water-driven feet. They work like this. Sea stars, and most echinoderms, are plumbed with a water vascular system that radiates as canals lined with tube feet down each arm from a central ring canal encircling the mouth. Seawater for the system is pumped in by cilia through a central sieve plate that looks a little bit like the drain



A sea star's water vascular system with tube feet, bulbs and the sieve plate.

in a hot tub, and distributed to the canals and tube feet. When you look at those wriggling tube feet, you're looking at the extremities of the water vascular system, and one of the marvels of the echinoderm way of life. The sea star in your hand has thousands of tube feet, each of which it can extend by increasing the pressure inside a little muscular bulb filled with water. This forces more water into the tube foot to extend it. Muscles in the tiny tube foot itself move it from side to side or retract it back up inside the arm. Tube feet on different parts of an echinoderm's body are modified for locomotion, adhering to rocks, pilings and other objects, breathing, burrowing, moving food around, sensory perception, or performing a combination of tasks. Some tube feet at the ends of a sea star's arms, for instance, have tiny primitive eyespots that can sense light. By coordinating the pressure in their vascular system and the muscular movement of all their tube feet, sea stars can move equally well in any direction, climb things, and clamp themselves tightly to stay put.

And they do it all without a brain. Using your X-ray vision (remember, you're imagining this) look inside the sea star. Instead of a brain, an echinoderm has a network of nerves that radiate in five directions from a central nerve ring encircling its mouth. This nervous system relays impulses from light, tactile, and chemical sensors around its body, acting as a kind of relay station rather than a central processing organ to coordinate the movement of its arms, feeding tools, and tube feet. If the radial nerve in one of a sea star's arms is cut, that arm will continue to move but in a different direction than that of the other arms still connected to the central nerve ring. If the central nerve ring itself is cut in half, the sea star may literally pull itself apart in two directions with the power of its tube feet that are no longer working together. However, this presents no real problem for an animal that can regenerate lost parts to make itself whole again.



Nervous system with nerves running down arms and central ring.

Most echinoderms can regenerate lost parts easily, and even create two or more animals from a single one. In a classic story of invertebrate revenge, fishermen pestered by infestations of sea stars routinely chopped them up and threw the parts back into the sea, wondering all the while why their problem kept getting worse and worse. Like all animal traits, the ability to regenerate evolved according to the rules of natural selection. Since most sea stars live in rocky shallow water subject to the violent combination of surf, surge, and boulders, those that could perform this remarkable act of self-preservation prevailed to become ancestors of future generations that would carry the ability to regenerate. And when a predator has a grip on one of your arms, what better way to escape than by simply leaving it behind? When an arm breaks off, the wound seals itself and a new arm begins to grow. Sometimes, both severed parts can grow entire new animals if each has at least a piece of the central disc. Some sea stars and other echinoderms actually use this regenerative ability as their main method for reproduction and creating successive generations-budding new parts that separate and become new animals. Echinoderms also reproduce sexually, although males and females look very much alike. They release eggs and sperm into the water and fertilization occurs externally, producing bilaterally symmetrical larvae that actually swim, propelled by minute cilia. These larvae metamorphose from their bilateral beginnings into the typical radially symmetrical adults, possibly in a replay of their ancient origins.

One of the things which is really fascinating about echinoderms is that they don't seem to grow old. They can live forever. They only thing that kills a sea star is physical or disease. Some sea stars can regenerate their whole body from one part of the ray. Just take a little ray, and cut it off, and the whole thing will grow out. How do they do that?

John Pearse, Biologist

Through most of our history of looking at echinoderms, it's been easy to think of these denizens of rocks, pilings, kelp forests and sea floors as brightly colored clumps that somehow make a living but don't do much in the way of interacting with each other or the rest of the ocean's flora and fauna. Only in the past half-century, really, have we been admitted into the world of five-sided living with scuba tanks and underwater movie cameras to witness first-hand the remarkable world of these silent, spiny-skinned creatures that took off in their own direction on the evolutionary trail. We now know that echinoderms invented as successful a set of solutions for meeting the challenges of life as any other phylum of animals.

We have not only picked up sea stars in aquarium touch tanks to marvel at their wildly different body plan, but with the help of time-lapse photography, watched them digest a mussel, or witnessed voracious, grazing sea urchins laying waste to entire kelp forests. Urchins, like all echinoderms, live on a scale of time that is very much slower than our own, a scale much more suited to life as a five-sided radial animal than one with a head and someplace to quickly go. Sea stars and urchins look like odd, colorful but inert objects sitting on the bottom, but filmed and viewed in time-lapse, they clearly demonstrate hunting, defensive, and social behavior as vigorous as any other animals.

Brittle stars

The smallest echinoderms are brittle stars, graceful ballerinas of the sea that defend themselves by shedding their arms. They make up for their size and fragility by covering vast expanses of the sea floor like a furry, waving carpet, delighting many a diver. With deep ocean submersibles, we have also spied on the secret life of sea cucumbers and found that they absolutely rule the bottom of the abyss. Without brains, eyes, or speed, these vacuum cleaners of the sea make up 90 percent of the living biomass on the deep ocean floor, which means they have essentially conquered two-thirds of the surface area of the planet. Sea cucumbers have taken an elongated version of the five-part, radially symmetrical echinoderm body plan, and adapted the tube feet at one end to shovel nutrient-rich sand into their mouths. No head? No brain? No tail? No problem.

Echinoderms are the Bohemians of the animal kingdom, but there is nothing about their history to suggest that they made a mistake in taking the road less traveled.

From top left clockwise: chrinoid; urchin; chrinoid; sea star; brittle star; sea urchin; shrimp living on a sea cucumber; sieveplate on sea star.