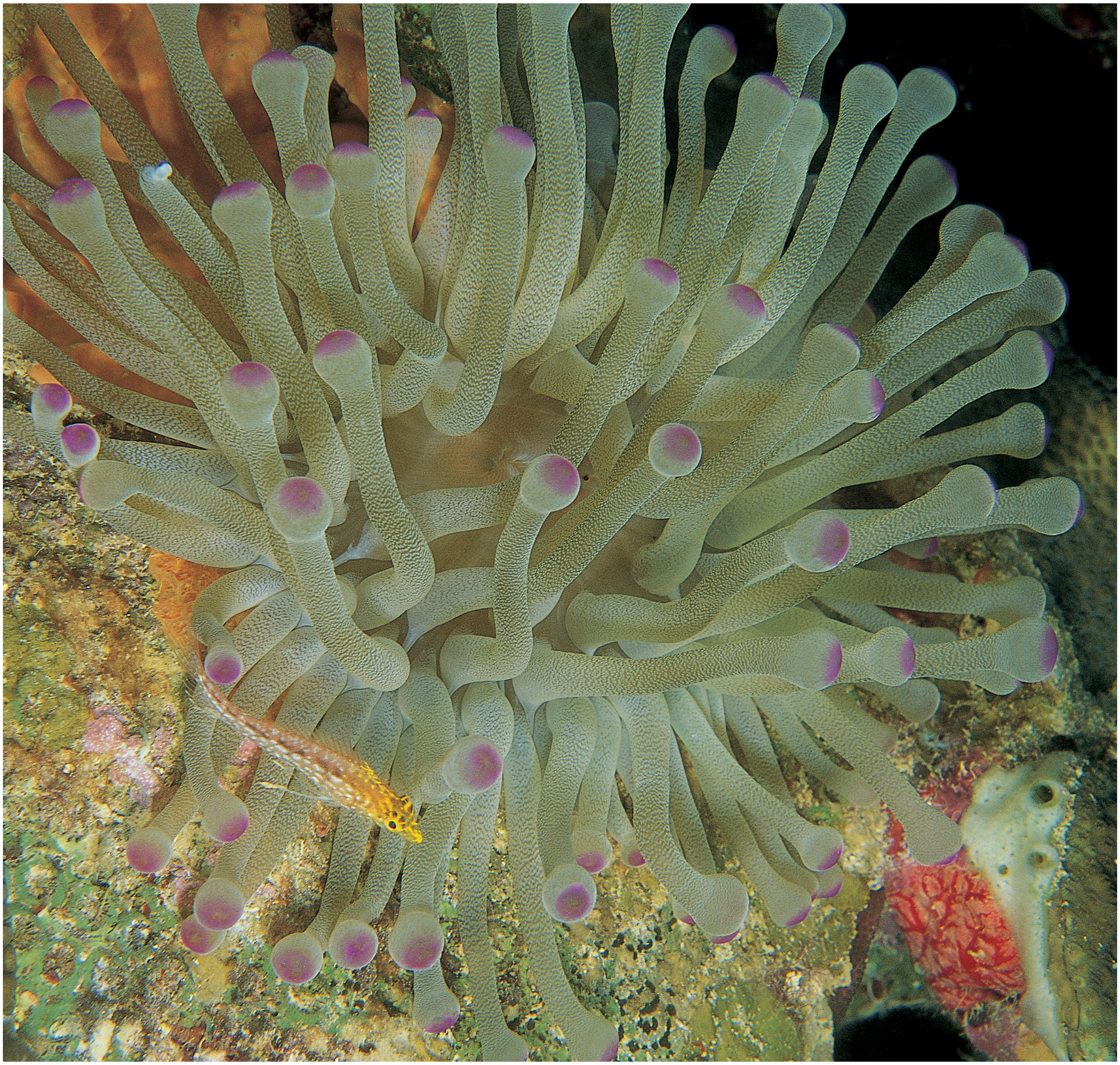
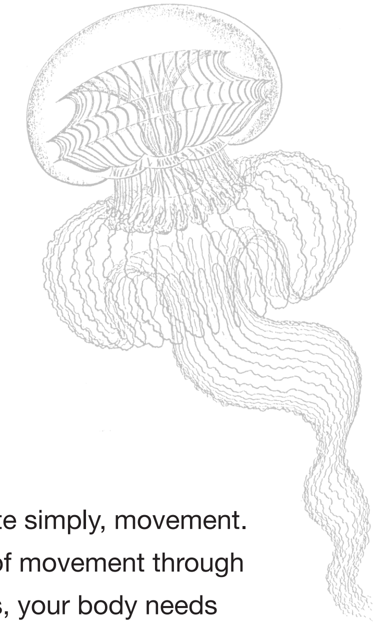
The Polyp and the Medusa
Life on the Move



Millions of years ago, unlikely pioneers sparked a revolution. Cnidarians set animal life in motion. So much of what we take for granted today began with Cnidarians.

FROM SHAPE OF LIFE



Life on the Move

Take a moment to follow these instructions:

Raise your right hand in front of your eyes.
Make a fist.
Make the peace sign with your first and second fingers.
Make a fist again.
Open your hand.

Read the next paragraph.

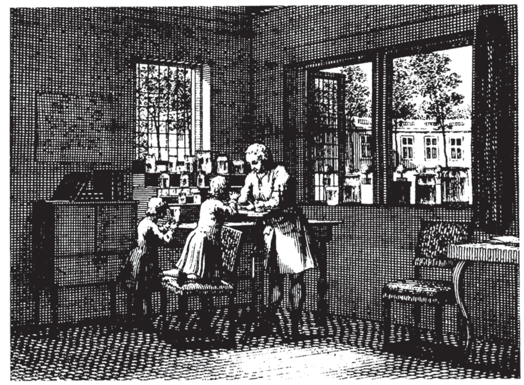
What you just did was exhibit a trait we associate with all animals, a trait called, quite simply, movement. And not only did you just move your hand, but you moved it after passing the *idea* of movement through your brain and nerve cells to command the muscles in your hand to obey. To do this, your body needs muscles to move and nerves to transmit and coordinate movement, whether voluntary or involuntary. The bit of business involved in making fists and peace signs is pretty complex behavior, but it pales by comparison with the suites of thought and movement associated with throwing a curve ball, walking, swimming, dancing, breathing, landing an airplane, running down prey, or fleeing a predator. But whether by thought or instinct, you and all animals except sponges have the ability to move and to carry out complex sequences of movement called behavior. In fact, movement is such a basic part of being an animal that we tend to define *animalness* as having the ability to move and behave.

Obviously, something changed since sponges led the parade of animal life on earth over half-a-billion years ago. The ancient Animal Eve was a barely differentiated collection of cells capable of transmitting messages only at the most primitive chemical level. It had no muscles or nerves. Though some sponges can slowly change location by literally building themselves out into a new direction, they don't do it by transmitting nerve impulses to command movement.

So why, when, and how did animals develop the ability to move?

What defines *animalness*?

Abraham Trembley was a Swiss scholar and teacher living in Holland. His insatiable curiosity about the natural world led him to lay the groundwork for a great leap in our understanding of animalness. To Trembley's contemporaries, a decision about whether something was an animal was elemental not only to their scientific understanding of life on earth, but to their theology as well. The word animal derives from the Greek word for soul – *anima*. Did all animals have souls? And if certain animals they had observed were able to regenerate themselves from buds or severed parts, did each new animal have a soul? Was there a soul in the part that regenerated? And, they wondered, how simple could an animal be?

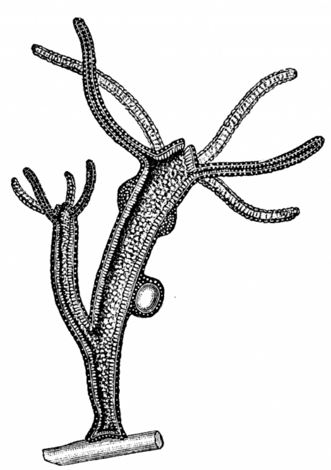


The little creature whose natural history I am about to present has revealed facts to me which are so unusual and so contrary to the ideas generally held on the nature of animals, that to accept them demands the clearest of proofs.

Abraham Trembley, 1744
Memoirs Concerning the Natural History of a Type of Freshwater Polyp with Arms Shaped Like Horns

Trembley was investigating life in a pond near where he lived when he came upon tiny, green, plant-like things that looked for all the world like tufts of grass. "The shape of these polyps, their green color, and their immobility gave one the idea that they were plants," he wrote. "This same initial impression was evoked in many people who saw the polyps for the first time when the creatures were in their most usual position. Some said that the polyps were bits of grass; others compared them to the tufts on dandelion seeds."

Then to his astonishment, he watched them move. "The first movement that I noticed was in their arms, which bent and twisted slowly in all directions. Thinking that they were plants, I could scarcely imagine that this movement was their own," he wrote in his now-legendary *Memoirs Concerning the History of a Type of Freshwater Polyp with Arms Shaped Like Horns*. The title of his memoir would hardly make Oprah's book club today, but in it he began to construct a bridge across the abyss that once separated human beings from their understanding of the origins of animal life and behavior.

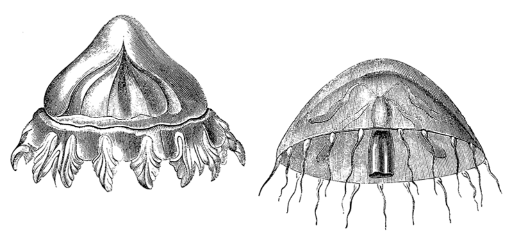


Trembley was a scientist, and like the modern members of this tribe of discoverers, he then made systematic observations to support his hypothesis that these freshwater polyps from his pond — now called hydra — were animals instead of plants because they moved and caught and ate prey. He took some of his subjects into his lab in a jar of water, offered them food, and watched them eat. He also placed a jar of them on the windowsill and noted that they moved slowly toward the lighted side. After weeks of painstaking study, he decided correctly that they were animals instead of plants, and the keys to his conclusions were that they moved and ate. "I saw them digest animals as long and even longer than themselves. Thus I had hardly any further reason to doubt that they were carnivorous animals," he noted.

Abraham Trembley's discovery that the green things in his pond were active, predatory animals was a revelation for eighteenth century science, but in the centuries that followed it would lead to even more profound conclusions about animal life: Their earliest ancestors, we would learn, invented nerves and muscles. The little creatures in his pond were polyps, members of the group of animal life known as cnidarians (ni-dar-eans) that includes not only his freshwater creatures, but the much more common saltwater polyps, including corals and sea anemones. In addition, there is the flip side of the cnidarian family -- the medusae -- most familiar to us as jellyfish.

Ancient cnidarians were pioneers of the complexity we now take for granted. All animals except sponges have nerves and muscles, and since cnidarians are the simplest animals to possess this complexity, their earliest ancestors were very likely the first.

Cnidarians are also the first animals with an actual body of definite form and shape. The presence of tissue allowed a body to take on a shape, a level of organization in which groups of cells of the same kind bond together to collaborate in performing the same functional chore. The invention of tissue allowed skin, muscles, and nerves to function in bundles, which are much more efficient than separate cells. This body also had the first opening we call a mouth and a digestive cavity, which would eventually allow cnidarians to become voracious predators. These cnidarian innovations were so radical and important to survival that they were passed down with increasing refinement to all other animals as they evolved through time.



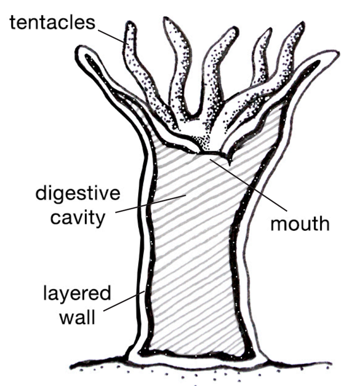
For me the really fascinating questions in biology are all about origins. Where have we come from? What sort of things started off the evolution of behavior? And you gotta go back to a group like the cnidarians in order to study this question.

Ian Lawn, Biologist

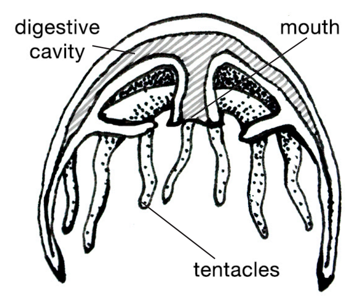
Two Body Plans

According to the fossil record, the earliest cnidarians made their appearance about 600 million years ago, most likely as fleshy polyps anchored to the sea floor in a world where nothing moved, swam or scuttled. Although no fossils of intermediate animals have been found, the earliest cnidarians may have evolved from sponges, driven by the constant pressures of survival and procreation to evolve additional specialized cells that became nerves and muscles. The reason we have so little evidence of early cnidarians in the fossil record is that the bodies of these simple creatures consist mostly of water and jelly, leaving few traces that survive through deep time.

This amazing body plan has evolved into the present in two different forms. They use the same functional structures, since the body plans are essentially mirrors of each other. By turning the same shape upside down, cnidarians invented two distinct ways of living. Polyps include Trembley's little pond critters and similar ones living in the ocean, along with anemones, and hard corals, Polyps feature cylindrical bodies with one end attached to the sea floor, a piling, rock or other surface, while the other end waves a tentacle-ringed mouth freely in the water. The medusae are their mirrors, mostly cylindrical but some shaped like cubes, with tentacles and mouth ends facing down. (The down-hanging tentacles resemble the snakes of Medusa's hair from Greek mythology, hence their name.)

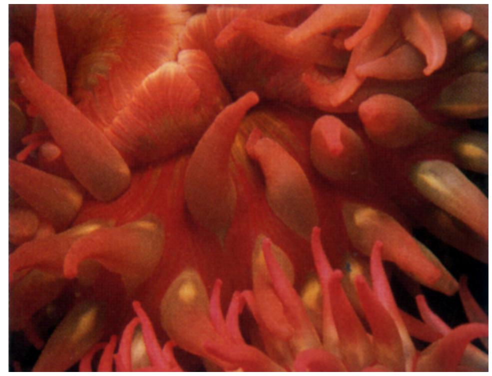


SIMPLE CNIDARIAN POLYP



IDEALIZED CNIDARIAN MEDUSA

About 10,000 species of cnidarians still populate the seas, lakes and rivers of earth, although most are marine. Trembley's freshwater polyps are a relatively minor branch of the group, and the jellies, anemones and corals are by far the most common. Whether polyp or medusa, all share the same basic architecture for living. Some are microscopic, some as large as three meters in diameter, but they are all radially symmetrical, with nerve nets for transmitting impulses in response to stimuli, a single body cavity, and an opening in the body that serves as both mouth and anus. This shape means that a cnidarian's body does not have a right or a left, but is the same all around, which is a smart way to live if you are attached to the bottom or drifting in the three dimensions of the ocean waiting for a meal to drift by.



Muscles and Nerve Pioneers

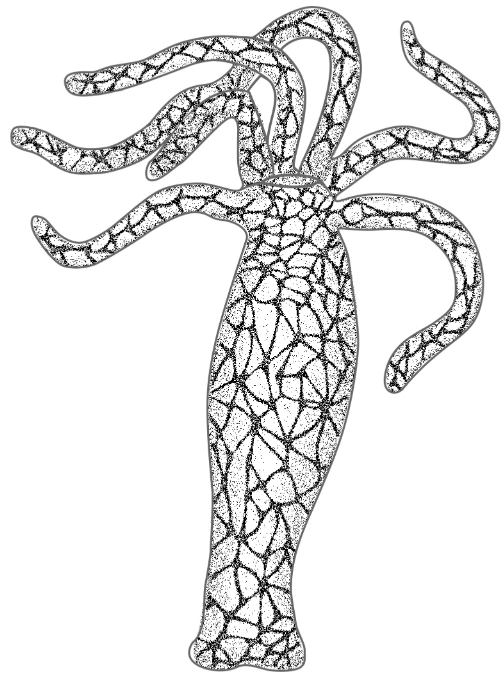
They are creatures so simple that scientists once considered them plants. But they're the critical group to study if you want to understand motion and behavior.

Jack Costello, Biologist

Ian Lawn, Jack Costello, and most other evolutionary scientists believe the appearance of early cnidarians about six hundred million years ago revolutionized animal life, but they don't have to be time travelers to study them. A common ancestor of the ancient hydra and medusa passed on inventions to entirely new kinds of animals -- including our vertebrate ancestors – but the basic cnidarian body plan – in both its forms, continues to exist.

Though they are ninety-seven percent water, cnidarian bodies are quite a bit more complicated than sponges. The body wall of a polyp or a medusa has two layers of cells, one specialized for protection that covers the outside, and an inner layer lining a stomach cavity for digestion. All cnidarians are carnivores. Meat-eaters. Digestion begins in the central cavity, a primitive kind of stomach, and is completed within specialized cells themselves. Whip-like flagella on the cells lining the stomach cavity keep the ingested food agitated and help distribute nutrients. Sandwiched between the inner and outer layer of cells is a layer called the mesoglea, which is thick and jelly-like, hence the name jellies given to many cnidarians. Though the mesoglea is mostly water, it also contains that wondrous animal stuff called collagen which gives it shape and elasticity far more durable than any shoe sole developed by Nike. The mesoglea, and everything else that makes a cnidarian, has to last as long as it lives, which in some cases can be a very long time. An anemone living at the Plymouth Aquarium survived for eighty years until the tank was accidentally drained, and the anemone died.

Muscles and nerves exist in their most primitive forms in cnidarians. Using two sets of muscles, a cnidarian can flex in a range of directions, lengthening or shortening its body. Their muscles, like yours, can only exert force by shortening, not lengthening, which means another set of muscles must provide the counter-force to move in the opposite direction. This other set of muscles also stretches out the opposite muscle so it can contract again. Your fingers extend from your fist to make a peace sign because nerve impulses command a set of muscles on one side to contract and pull the finger straight up. They return to form a fist again when a different set of muscles on the other side contracts to pull the fingers back into your palm.



All of this is governed by the electrical impulses carried by nerve cells. In humans, the nerves extend from a central nervous system but in cnidarians, the nerves form a network with no center. If the outer layer of a cnidarian comes in contact with something that is not itself – be it prey or predator – special sensing cells begin the chain reactions that radiate electrical impulses through the nerve net, stimulating the muscles to contract. Neurobiologist Ian Lawn did a simple experiment with an anemone, Stompia, to try to understand how an animal with a simple body plan and nervous system is capable of complex behavior. Underwater we see Stomphia free itself from a rock and swim away to escape from a predatory sea star. In the lab Lawn conducts experiments to record the nerve activity of feeding and escape behavior. His recordings reveal that the same nerves are firing more rapidly when the animal detachers from the rock and swims than when the animal feeds. The nerve impulses are the same size: it's the frequency of the firing of the nerve cells that carries the information about the intensity of the signal. The nerves in all animals, including in our bodies, work the same way.

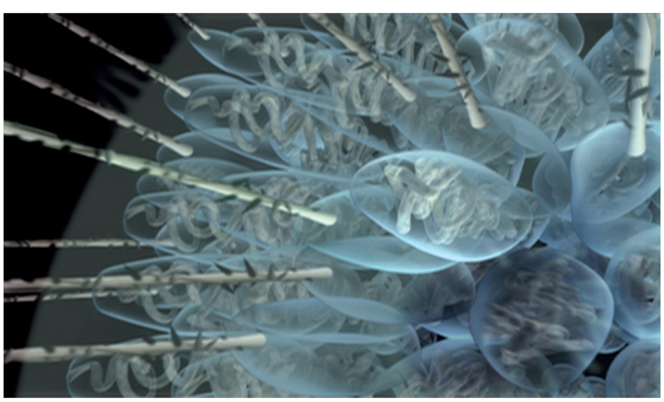
Muscles alone, though, would be useless if they couldn't contract against something we know as a *skeleton*. We have bones to which our muscles are attached and against which they can apply force to produce movement. So where is the skeleton in a blob of water and jelly? Remember that beautiful purple-and white anemone you saw once in a tide pool or clinging to a dock piling? If you watched long enough, you saw it grow longer and bend in one direction or another, then retreat and do all of that again. It was actively feeding, not just waving in the current, and to do that it used its muscles working against a skeleton made of water, called a hydrostatic skeleton. In that anemone, and all cnidarians, the central cavity is filled with water. Its body works like a water balloon when you squeeze it. The water is held in by

the skin of the balloon, so when you squeeze it, the balloon grows longer at the top and bottom. In a cnidarian, say an anemone anchored to a rock on the sea floor, one set of circular muscles that wraps around the animal's body contracts (as though squeezed from the outside) and the anemone's body extends up to become taller and thinner. Another set of muscles that extends from the top to the bottom contracts and the anemone becomes shorter and fatter. If the muscles that run from top to bottom contract on one side only, the anemone bends toward that side. The tentacles of anemones and other cnidarians have similar sets of tiny muscles for extending or contracting.

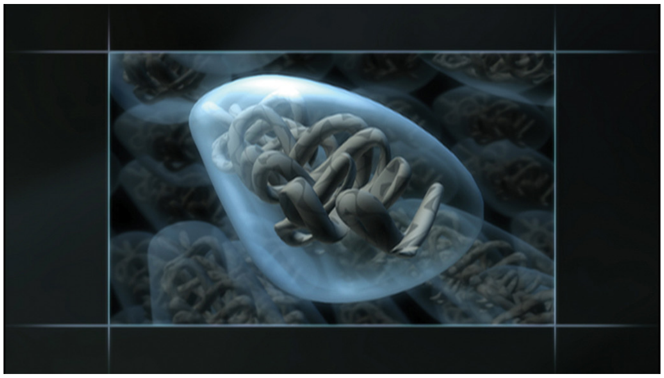
Jellyfish pulse using a very different system. The jelly in their bell is elastic, so the contracting muscles put tension on the bell. When the muscles relax, the elastic bell bounces back to its original position, stretching the muscles out so they can contract again. The jelly's muscles contract, relax, contact, relax, on and on, as it pulses through the water.

Stinging Cells: Nematocysts

Imagine that you are a carnivore and spend most of your time either anchored to a reef or the sea floor, like a coral polyp, or pulsing through the water, able only to respond to contact but unable to actually pursue prey, like a jellyfish. What would you invent to get a meal? You can't grab your food with powerful muscles, but what if your food simply sticks to your tentacles when you touch it? Cnidarians have a secret weapon that allows them to do just this, one that is familiar to anyone who has ever paddled through a raft of jellies, or scuffed a bare leg against a coral reef. From specialized cells called nematocysts, all cnidarians fire microscopic harpoons that capture and hold their prey. Many are laced with toxins that can kill or cripple animals much larger than the cnidarian itself. Honest. (Their name comes from the Greek word *Knide*, which means 'nettle.')

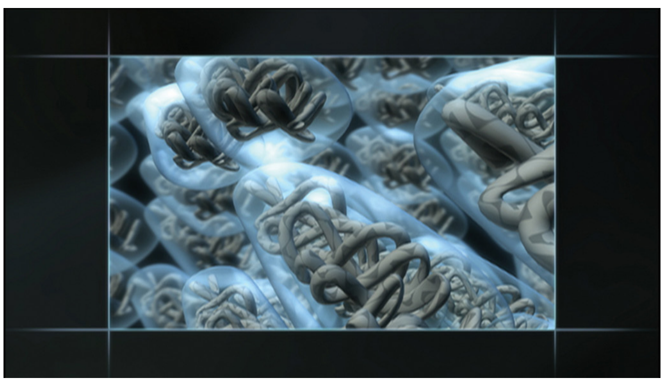


Until the invention of modern high-powered microscopes and ultra-high speed photography, nematocysts remained veiled in mystery. All we knew was that jellies, corals and anemones stung their prey, and sometimes us, with deadly results. Now, though, we can see the cnidarian arsenal in



all its incredible variety, looking like a nightmare of medieval weaponry. We have also actually observed them at work, firing out of the cell sac with the acceleration of a pistol bullet at nearly 40,000 times the force of gravity, everting a hollow filament through which poison is injected when the harpoon hits its target.

After the nematocyst silos are empty, the nematocyst-growing cells, called cnidoblasts, have to grow new ones before the next attack. And because each nematocyst can fire only once, it must not do so indiscriminately. If a jelly brushes against the glass wall of an aquarium, for instance, its nematocysts will not fire. If it touches a potential meal or enemy, only the nematocysts in the immediate vicinity of the stimulus will fire. There is no evidence that the stimulus signal is passed to other parts of the body, which means that each nematocyst cell is independent, containing within itself the sensory properties required to fire. Most likely, a nematocyst is able to chemically differentiate between the animate and inanimate stimulator, a very sophisticated bit of work for animals that look pretty much like The Blob.



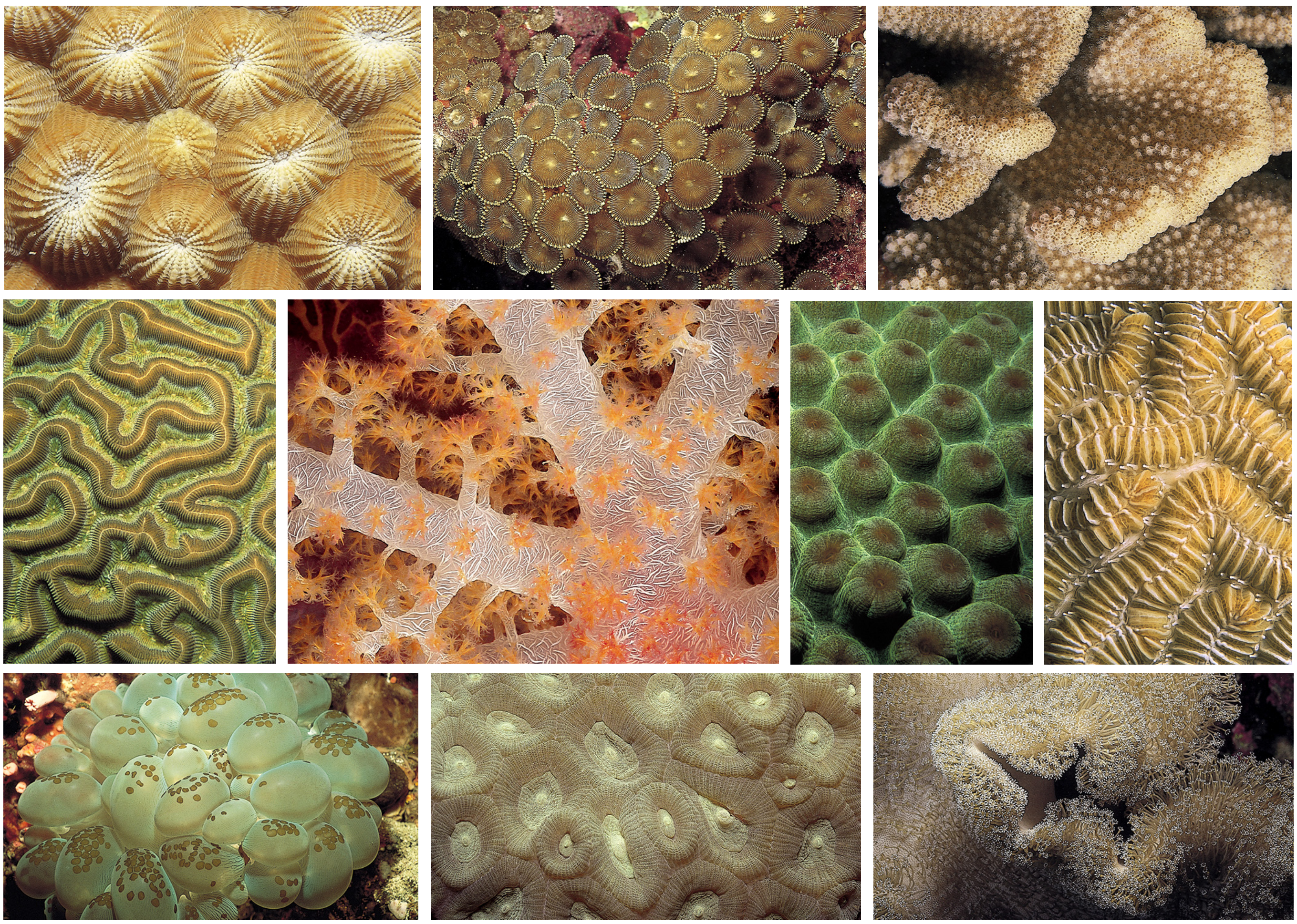
Nematocysts are among the most complicated example of cell specialization in the animal kingdom. Without nematocysts, cnidarians would lead very different lives. The Defense Department spends billions of dollars trying to develop weapons as effective as nematocysts, but those brainless wonders did it many times over to adapt to the characteristics of their targets. The harpoons of some nematocysts are perfect for piercing fish scales, some for combat with other cnidarians in turf battle, some for penetrating soft flesh. The toxin they inject can be powerful enough to kill a human being. The cubomedusae, or box jellies, of the waters off northeast Australia claim twice as many human victims as sharks. On the other end of the scale, the nematocysts of most of the anemones we touch in tide pools are so small we barely feel their effect, only a kind of tingling stickiness.

If you touch an anemone with your tongue, though, you'll definitely get stung because the softer, tasting tissue of your tongue allows the harpoon to penetrate. ***(Do not try this.)*** Though nematocysts are chiefly weapons, cnidarians have adapted them to other uses as well. Hydra use them to attach themselves while moving. Some anemones use them to build tubes of mucus in which to live. Others, like siphonophores, dangle lures loaded with nematocysts to attract their prey.

Cooperation Not Aggression

As warlike as all that harpooning and poisoning sounds, cnidarians can be among the most cooperative animals on earth. One of the most dramatic examples of their cooperation, Australia's Great Barrier Reef, was created over millennia by miniscule corals forming huge colonies that can be seen from orbiting spacecraft.

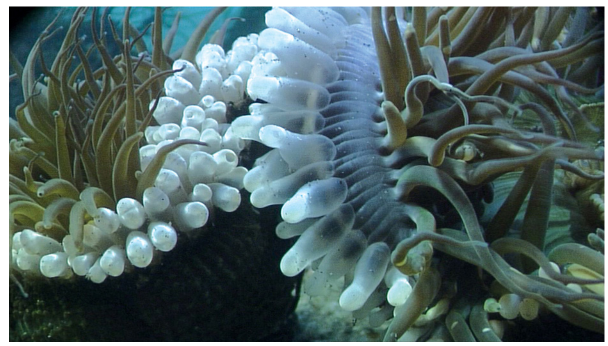
These particular little animals are polyps that reproduce by dividing in half over and over to create new members of the colony, remaining attached to their offspring while building the structures we call reefs. Just one of these coral colonies can contain millions and millions of individual animals, joined together forever. The surfaces and crevasses of a reef are covered with living corals, built upon the hard bodies of their departed brethren who have turned into limestone.



And not only do the hard corals of a reef colony work together to increase their chances for survival, but within each tiny polyp is another example of cooperation. All corals play host to symbionts, called zooxanthellae, which are tiny photosynthetic algae. By teaming up with zooxanthellae, corals guarantee themselves a supply of the nutrient-rich by-products of the algae and oxygen to supplement the rest of their diet of larvae and other small bits of drifting, organic matter captured by their tiny, nematocyst-studded tentacles. The corals, in turn, offer these precious solar collectors nitrogen, carbon dioxide, and a sheltered place to live within their colossal reef castles.

Love among the cnidarians is also a cooperative affair and about as diverse as you can get. Some species of the medusa side of the family are hermaphroditic, some have separate sexes, and most reproduce by broadcast spawning. Sperm and eggs are cast into the water, and the lucky ones get together. Some polyps, such as corals, also spawn by broadcasting sperm and egg, and their sex act is orchestrated by moonlight or other environmental cures. Most tiny hydra produce daughter polyps, which simply pop-off from their parents, especially when times are good and the water's full of food. Some anemones reproduce by cloning themselves, asexually dividing into exact copies of themselves and forming dense colonies to control large areas of turf on the sea floor.

Clone wars occur between different colonies from time to time, when an anemone from one colony tries to encroach upon another's territory. For these battles, the anemones use specialized fighting tentacles spiked with nematocysts. The conflict can go on for days before one has been stung enough times to force retreat.



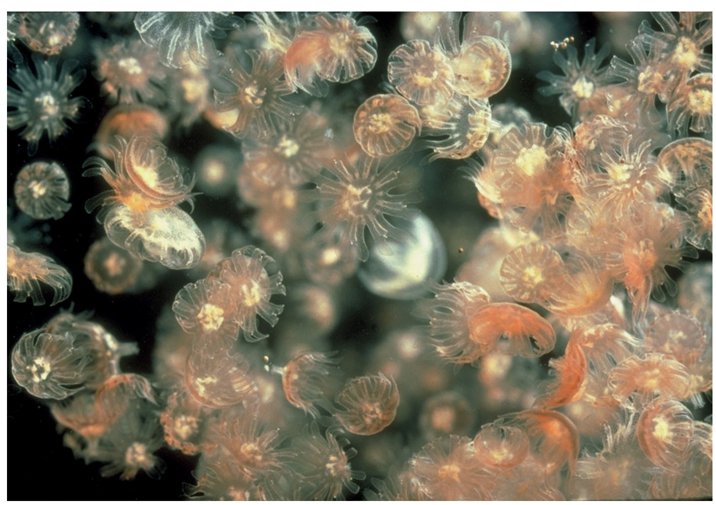
Which Came First-the Polyp or the Medusa?

As is always the case when investigating mysteries through the lens of deep time, there is still debate over which came first, the polyp or the medusa. Most bets are on the polyp. And then, although no one is sure exactly when or how it happened, some of these anchored cnidarians took off in a dramatic new direction. Equipped with primitive nerve nets and muscles that could flex in response to stimuli, and urged by the power of natural selection, the edges of their mouths extended and developed arm-like feeding structures. The jellyfish had arrived on earth. The polyp's food-grabbing tentacles became long, thin strands, the cylindrical stalk of their bodies became a gelatinous bell, and the familiar, ghost-like jellyfish took shape, thrived, and proliferated. The medusae may have been among the first animals to actually swim the world's oceans, where they remain today as the top predators in the food web.

Because cnidarians are still around, we can watch a wondrous echo of that moment of transition from polyp to medusa that happened - so long ago. The polyps that best demonstrate the transformation from polyp to medusa – in a process called strobillation – are so tiny that they have to be grown in the laboratory and closely watched to see in action. They are called moon jellies, and like many medusae, begin their lives as tiny polyps, anchored to a rock or other solid surface on the ocean floor. A few times every year, triggered by the rhythms of the sea, they undergo a transformation that very likely mimics the emergence of the first medusa over half-a-billion years ago. The polyps are as different from moon jellies as caterpillars are from butterflies, so different and so small that the polyps of some species of jellies have yet to be discovered.

“It’s a phenomenal process. At some point, those polyps begin to divide,” says biologist Jack Costello, “and it’s almost like they form little plates, one on top of each other. Each polyp forms dozens of orange-colored plates, and each plate pulses like a baby bird trying out its wings at the edge of its nest until in turn it breaks off and becomes a single animal, called an *ephyra*. Over the course of a month, the tiny juvenile jellyfish feed on plankton as they develop into adults and can grow from a diameter of one millimeter to two feet in just a month. Watching this happen is like riding a time machine into the deep past to the moment when polyps first rose from the sea floor to become the swarms of drifting predators that we know today.

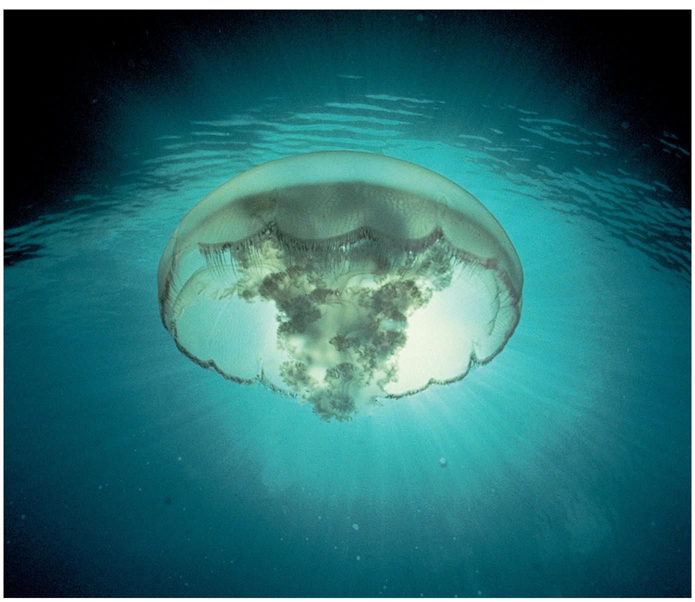
The process begins anew when the adult moon jellies gather in massive swarms in coastal shallows. The males cast threads of sperm into the water; the females collect the threads with their frilly arms and ingest them, fertilizing their eggs. The eggs develop into simple balls of cells that swim free from the mother medusa to settle on the sea floor and grow into a tiny polyp. Within days, the bodies of some of the mother jellies begin to break down and disappear, but their offspring will live for years, budding tiny jellies to populate the oceans.



Jellies on the Move

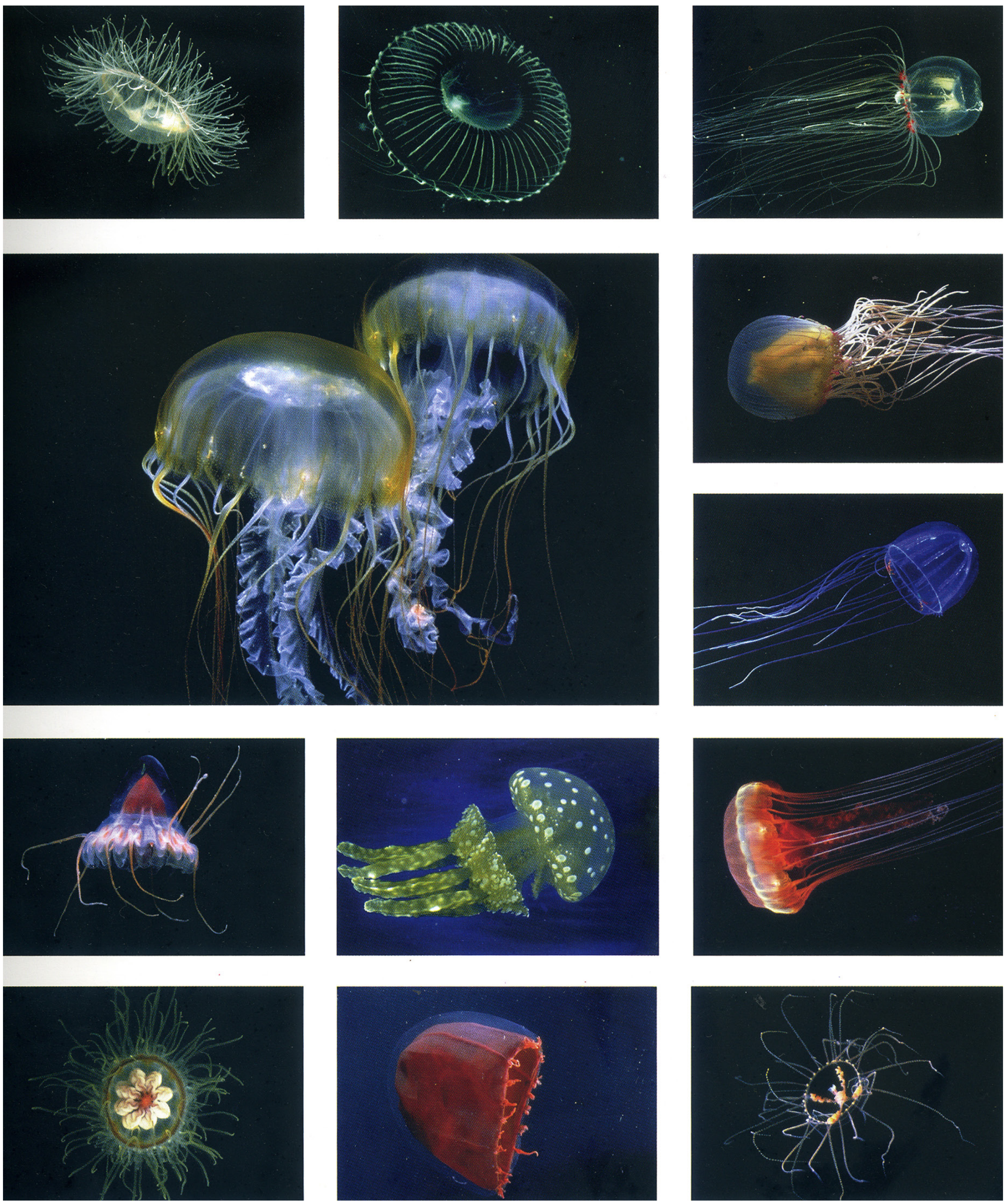
The life cycle of moon jellies is natural magic, but the swimming behavior of the adult jellies also intrigues Jack (See Shape of Life Scientist video: Jack Costello - shapeoflife.org/video/jack-costello-biologist-why-jellyfish-swim). He enters their watery world with diving gear and brings back their stories with a digital camera, capturing hours and hours of their behavior. They seem to swim almost constantly, but they go nowhere. The jellies expend enormous amounts of energy to move. So what do they get from moving? "They do spend all their time swimming, and they really don't make much forward progress," Costello says. "That leaves us asking, why would they spend their time swimming?"

This is a classic statement of a puzzle of form and function: Does the jelly's form serve a function that is not immediately obvious? All animals balance their food and energy budgets to produce a net gain by growing larger, getting stronger or faster, and, on the bottom line, surviving. Obviously, jellyfish are survivors.



But Costello was confounded because the bodies of jellies do not seem to be designed for easy movement through the water. In fact, their body plan seems shaped to slow them down. "That round disk shape is probably one of the least effective shapes for forward progress that we can imagine. A flattened shape moving through the water presents the most resistance, in what we call drag, of any form you can imagine," Costello says.

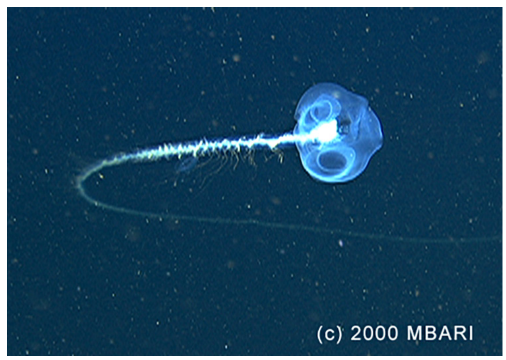
In a highly refined echo of the methods of observation pioneered by Abraham Trembley, these observations depend on systematic inquiry to either support or disprove an hypothesis, the self-correcting process known as the scientific method. And we have come a long way from experiments conducted in jars of water sitting on a windowsill in the sun. Instead, in a modern laboratory, we can record and analyze the cnidarians in carefully controlled tanks that mimic their life in the wild. "What we wanted to do was look at the action of swimming and look at how the jelly interacts with the fluid around it." His subjects this time were the size of water drops. Into the tank with the jellies, Costello added tiny, visible particles, which allowed him to actually watch and videotape the flow of water around the animals. As the jellies swam, they created a visible current, and it was in their creation of that current that he found the solution to his form-and-function puzzle. “What we found looking at it is that this very high drag body form is very good at creating vortices and flow around the bell margin,” he says. “It’s the flow created by swimming that is bringing all the prey into the capture surfaces. The body we think of as bad or ineffective for forward motion is very effective for creating the flow which enables the animal to feed.” As the jelly’s bell pulses, the water flows in under the bell margin through the tentacles, bringing food particles in contact with both the tentacles and the oral arms, where nematocysts can shoot their harpoons to capture prey.



Figuring out what a jelly gets from a round body that doesn't get anywhere provides insight into their origins, too. The first animal to launch itself from the sea floor – perhaps at the budding end of a creature like a moon jelly polyp – may have done so to ensnare prey, not to give chase. "It's an incredibly simple but very effective system," Costello says. "It becomes a little more sinister when you realize that it is the mechanism by which these animals move through the water and essentially kill all their prey." The size and shape of the bell of each species of jellyfish determines the flow pattern around the animal, which means that each mines a particular niche in the ocean food web.

Because of their incredibly simple but very effective system for living in the sea, cnidarians have flourished as predatory carnivores. In today's oceans, these durable, successful animals mark time in centuries and have assumed forms that take advantage of an enormous spectrum of ecosystems, from the patient anemones of the tide pools to the giant jellies of the open ocean depths. Some are utterly startling. As we already learned, the anemone called *Stomphia* looks vulnerable as it sits anchored to a rock on the ocean floor, but it defends itself by detaching from the rock and swimming. Actually swimming.

The longest animal in the world, even longer than a blue whale, is *Praya*, a combination of the two basic cnidarian shapes: the pulsing bell of the medusa and a long train of stalk-like polyp tentacles. A single colony of these animals may be 120 feet long. Strung like a giant fishing net through the water, *Praya* feeds itself by chancing into prey and stinging them to death. Another medusa, *Colobonema*, has evolved a surprising line of defense. When startled, it detaches its tentacles and leaves them behind as decoys to distract would-be attackers.



All of their remarkable behavior and successful living for more than half-a-billion years, though, rises from the cnidarian's ability to move. Yours, too.

Take a moment to follow these instructions:

Raise your right hand in front of your eyes.

Make a fist.

Make the peace sign with your first and second fingers.

Make a fist again.

Open your hand.

Say: "Thanks, Cnidies."