The Land Arthropods

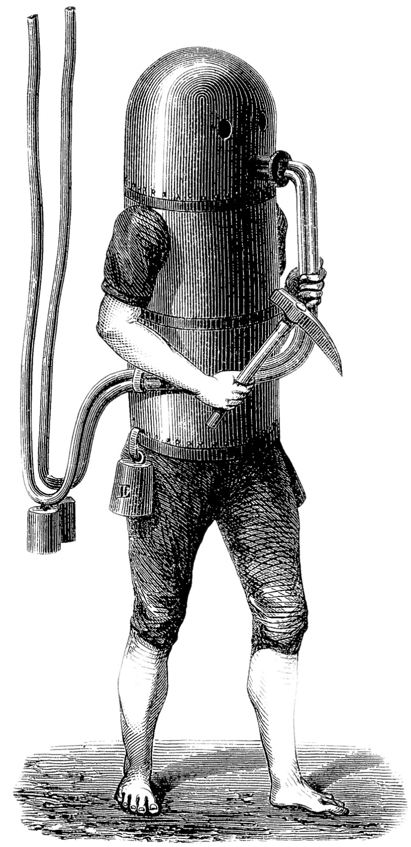
The Conquerors Coming Ashore

Life's transition from the sea to the land was perhaps as much of an evolutionary challenge as genesis. What forms of life were able to make such a drastic change in lifestyle?

JANE GRAY AND WILLIAM SHEAR "EARLY LIFE ON LAND," *AMERICAN SCIENTIST*

All life on earth began in the sea. When the first animals made landfall, obviously they had to evolve ways to move around and breathe in a place where oxygen is delivered in a much different way than in the water. When we try to go back to the sea, our chief concerns for survival are figuring out ways to breathe and move around and sometimes, avoiding being eaten. The human desire to submerge in water and still be able to breathe has probably existed as long as we've been diving to gather food, repair (or sink) ships, and marvel at the wonders of a world so different from our own. Getting past the fear of the unknown that lurks in the water is no small feat, since the sea is as alien to us land-dwellers as the surface of Mars, and is full of monsters that are, of course, waiting to kill and eat us.

Still, early on we hungered for a look into that utterly hostile environment, and as soon as our ancestors overcame the terror of the deep, we discovered that we could submerge for a frantic minute or two by simply holding our breath. Breathing through reeds and tubes is an obvious second step, but that limits us to a few feet because the pressure differential makes it impossible to suck air much beyond that depth. (Try it some time.) Breathing from bags of air doesn't work, either, because the build-up of carbon dioxide will kill you pretty quickly. By the sixteenth century, divers were using suits of leather and surface pumps that forced air through hoses to remain at depths of up to 60 feet for a few minutes at a time. That technology evolved into the twentieth century when hard-hat divers routinely ventured beneath the sea to work and explore. Submarines and diving bells followed, some served by air pumped from the surface, some by compressed air carried in tanks on the deep-sea craft themselves.



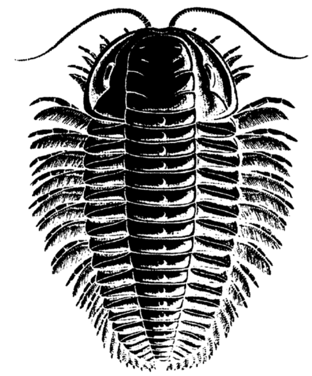
Drawing from Scuba Diver Life

Modern dive equipment

Finally, in the mid-1930s, an American aviator named Guy Gilpatric living in southern France pioneered the use of rubber goggles with glass lenses for skin diving. Frenchman Louis de Corlieu invented swim fins. In 1938, Gilpatric wrote about his new diving gear and exploits in The Compleat Goggler, the first book on underwater diving and hunting. Among the book's readers was a young French naval lieutenant named Jacques Cousteau, who would eventually invent and patent the Aqua Lung, a demand-regulator to be used with tanks of compressed air. He became the world's first enviro-celebrity, and ever since, human beings willing to wear rubber suits, masks, fins, buoyancy control devices, and tanks have been breathing, hunting and exploring under water. But that's the best we can do.

Earliest Arthropods

The history of the animals whose descendants would be the first to breathe air and live on land begins over half-a-billion years ago, when the earliest members of a group called arthropods branched off from their ancestral roots of primitive, bilateral animals. These creatures quickly became powerful hunters and scavengers, and established patterns of adaptability and dominance that continue into the present. One group, the trilobites, were the top predators in the sea for more than 325 million years, beginning in the Cambrian when their primitive legs, complex armored bodies, and the first true eyes in the animal kingdom gave them immense power over less-endowed prey. Trilobites look a bit like modern pill bugs common in gardens, but they are only distantly related. Still, just about everybody knows what a real trilobite looks like because there were simply so many of them and because their hard shells endured through time as perfectly preserved fossils. Trilobites have been mined from quarries by the millions to be sold as paperweights, pocket rocks, tie tacks, cuff links, necklaces, and bracelets in just about every rock shop in the world. These rulers of the sea achieved immense diversity, branching into thousands of species over time. They and their other arthropod cousins began the noble lineages that would lead to the crustaceans, which include crabs, lobsters, shrimp and barnacles; the arachnids, which include spiders, scorpions and mites, and the largest group of all, the insects and their close cousins the millipedes and centipedes. But these arthropods were all marine creatures capable of living only in the sea. Life on land so far was limited to mats of bacteria and algae, low-lying lichens and very primitive plants.



Trilobite

And so it was when the first arthropods came ashore about 400 million years ago.

Jointed legs

During the two-hundred-and-fifty-million years or so after arthropods first appeared in the ocean, their basic body plan adapted to an enormous variety of niches in which they were able to live, creating new species and groups of species. The first members of their group had inherited their biological architecture from more primitive bilateral ancestors. With these coded instructions carried in every cell and controlled by those mighty Hox genes that choreograph the building of a bilateral body, the earliest arthropods took the basic ingredients of a segmented body – appendages, tissue, organs, nervous system and brain – and diverged to become an entirely new kind of animal.

> *Whatever criteria for success one cares to adopt, the animals with legs keep coming out at the top of the list. Whether one rates success in terms of numbers, number of species, range of habitats exploited, or simply as total mass of animal tissue, the limbed creatures clearly have the advantage.*
>
> Martin Wells, Lower Animals

The arthropod body plan has adjusted itself many times since it first appeared, adapting to the pressures of changing environments, the dance of predator and prey, and even the challenges of living on land. But then, as now, it was defined by a segmented body, jointed legs, and a hard external skeleton. The name, Arthropod, means 'jointed leg.' From its Greek root we also get the modern word art, which in its conception was defined as a joint between reality and abstraction. Although arthropods were immensely successful in the water, their bodies would eventually prove adaptable to living on land, too. Arthropods were, and continue to be, nature's greatest generalists: a fact that has contributed immensely to their success. The more specialized a group of animals is, the less able it is to cope with change once the inevitable happens and old habitats change beyond the point of supporting a particular life and body style.

Each key element of the arthropod body plan eventually contributed to their ability to make that transition from the sea. First, the segmented body is a powerful arthropod evolutionary tool that is common elsewhere in the animal kingdom. People are segmented, too, though not as obviously as earthworms or lobsters, and you have to know how to look at our spine and muscles to see the segmentation. This kind of construction allows a body to build itself in identical segmented units that become specialized for particular functions. Many of the tasks of living, like eating or sensing the world, are handled by appendages attached to each segment of the body or the head of an arthropod. These appendages, in turn, are segmented, which makes them both flexible and easily altered to become antennae, claws, jaws and other mouth parts, and especially legs—legs for walking, legs for clinging, legs for holding onto egg sacs, legs for swimming, and legs for digging. These corresponding appendages are said to be serially homologous, that is,

Various terrestrial arthropods: (from top) damselfly, spider and monarch butterfly similar in position on a particular segment but not necessarily similar in function. Their segmented legs allowed arthropods on land to counter the force of gravity and hold their bodies off the ground. And the joints would prove to be excellent shock absorbers for walking over rough terrain. Instead of just slithering and crawling, legs allowed arthropods to jump and walk and run at high speed and, eventually even evolve wings to fly.

Arthropods with jointed legs. Credit: Bugboy52.40 (Derivative from images uploaded by Fir0002.) via Wikimedia Commons

Skeletons on the Outside

> *There are good biological reasons why insects aren't the size of mobile homes and Greyhound busses and the like. One thing that keeps them small is their exoskeleton. It has to be molted and this presents insurmountable difficulties to insects as they get bigger.*
>
> May Berenbaum, Entomologist

Arthropods were the first bilateral animals with exoskeletons, in their case hard shells made of a nitrogen-rich sugar called chitin. In the simplest of terms, this suit of armor keeps the inside in and the outside out, and was perfect protection from the drying effects of air on land. It also anchors the muscles of claws, legs and antennae against which those muscles can work. Inside, an arthropod has all the organs of a complex higher animal, but its blood just sloshes through loose channels surrounding these organs, unlike our refined circulatory system that distributes blood throughout our bodies under pressure.

A grasshopper molting

One of the enormous drawbacks to life with a hard shell is that once it forms and hardens it doesn't grow, unlike our own internal bones, which are surrounded by flesh and organs but grow as our bodies grow. It's impossible, therefore, for the animal to grow for very long without just filling up the shell. Arthropods deal with this apparent design flaw by shedding their exoskeletons when their insides grow too big for their outsides in a process called molting. It's one of the most fascinating tricks in the animal kingdom. When a grasshopper, for instance, is plumped up against its shell to the point of bursting, it forms a new exoskeleton beneath the old one and separates the new from the old. What happens next is some complicated chemistry, controlled by special molting glands and hormones. The grasshopper basically loosens itself and its still-soft new exoskeleton from every part of its old hard body and legs, and slips out of its old shell in about forty minutes. Some take more or less time to do the job, but before the new exoskeleton hardens, they quickly expand their body to make sure the new hardened skeleton has extra room for growth. While molting is underway, arthropods are extremely vulnerable.

Even though arthropods have solved the problem of growing from juvenile to adult by periodically molting, their hard, heavy shells are one of the reasons Hollywood nightmare visions of giant insects terrorizing the world could never be real. Among the smallest of arthropods is a mite that lives on your eyelashes, and the largest is a crab with a twelve-foot leg span. All the bigger arthropods still live in the ocean, where the buoyancy of water reduces the force of gravity and the effort needed to pack around a heavy shell. This allows them to convert the energy they would otherwise be using for hauling themselves around into growth.

Another reason an arthropod could never be the size of a Tyrannosaurus rex is that its legs are much too fragile to bear a lot of weight. Jointed appendages are perfect for facile movement and speed up to a point, but balancing a lot of pressure on them is impossible. An apt comparison is the ability of the broad flat surfaces of hiking boots to carry more weight than a pair of high-heeled tango pumps.

But what limits the size of the most successful arthropods on land, the insects, is the way they get their oxygen.

Breathing Underwater

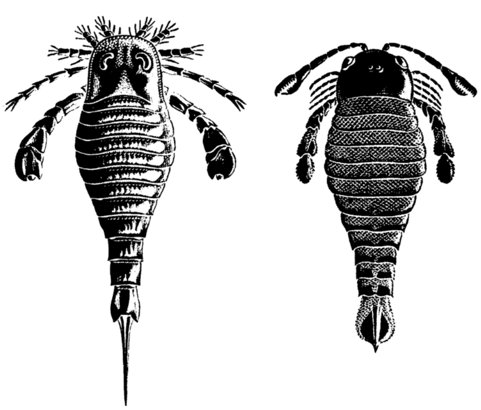
> *Take the simple matter of breathing. . . .Gills are simply useless for taking oxygen from the air.*
>
> Niles Eldridge
> Life Pulse: Episodes from the Story of the Fossil Record

Arthropods, like all animals, must find ways to extract oxygen from either water or air and distribute it to all parts of their bodies. In water, which contains forty times less oxygen than an equal volume of air, the standard tools are gills. A simple oxygen concentration gradient between the interior of a respiratory system and the open water allows gills to draw in oxygen molecules from the water through a thin membrane. The oxygen dissolves in the blood's fluids and is then whisked away to all parts of the body. Some marine arthropods, breathed with a system called book gills, which are just a row of flaps kept in constant motion so an ample supply of dissolved oxygen can enter the respiratory system. The marine ancestors of both scorpions and spiders had these book gills, which evolved into book lungs when they came ashore.

So with segmented bodies that turbo charge their ability to accommodate environmental changes, with legs that let them walk; with hard, waterproof shells that keep water in or out; and with highly adaptable respiratory systems, arthropods were prime candidates for colonizing land. It was only a matter of time.

On to Land

Some of the first signs of animal life on land look like scratches in rocks that had formed about 400 million years ago during the early Devonian, a time named after the part of the British Isles where those rocks were first discovered and dated. These scratches are very different from the trackways left by worms on the sea floor because they were clearly made by animals with legs, most likely members of a branch of the scorpion family called eurypterids. By the time they came ashore, whether fleeing enemies, in search of an easy meal, or to find a safe place to lay their eggs, the eurypterids had already established themselves as fierce and successful killing machines in the ocean. Some of them grew as long as six feet, equipped with legs, swimming paddles and claws that could crush just about anything in the sea. As Simon Braddy, a paleontologist who studies these ancient monsters put it, "One of the things that I like to say is that I'd much rather be in a pool with a six-foot shark than a six-foot eurypterid."



Eurypterids

There is little doubt that eurypterids made landfall just before the Devonian. They were well equipped as pioneers of life on dry land with the basic arthropod tool kit: legs; a hard shell to keep their bodies from drying up; and book gills that could function while merely moist and not completely immersed in water. But these adventurous eurypterids never completely abandoned their home in the sea to become terrestrial. Their relatives, the scorpions, however, would eventually become fierce predators on land.

Adapting to life on land is still a more difficult step. Temperature ranges are even more extreme, drying is a constant threat and respiratory mechanisms must be modified to use air.

Ralph and Mildred Buchsbaum & John and Vicki Pearse
Animals Without Backbones

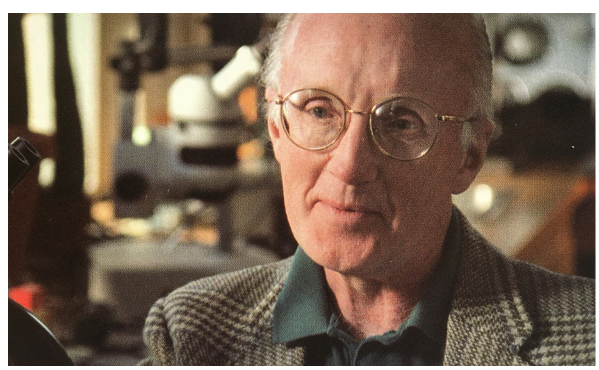
The first real colonization of land by animals that stayed would be made by much smaller explorers about 40 million years after the euypterids came out of the sea for a look. A series of relatively recent fossil finds reveal a complicated sequence of events. There are four major forms of terrestrial arthropods -- insects, millipedes and centipedes, spiders, and scorpions – so we know that arthropods had diversified before they made landfall and pursued parallel evolutionary trajectories both in the sea and ashore. And now there is ample evidence that arthropods invaded the land many times over.

What Animals Were the First to Crawl On To the Land?

What forms of life were able to make such a drastic change in lifestyle?
Bill Shear, Biologist

Bill Shear is a biologist whose interest in the evolution of insects and spiders led him into the search for their origins through paleontology. And as he examined the histories of the earliest land-dwelling arthropods, he also paid particular attention to the conditions that existed on earth at the time they left the sea. “The world of the Devonian was probably different from our world in many, many aspects,” he says. “The year was shorter and the days were not twenty-four-hour days. You’d have a different atmospheric composition. The plant life would look different, strikingly different.” It was among fossils of this first plant life that the tiny remains of those first invaders were found.

Obviously, the arthropod colonization of land was not just a matter of a couple of bugs just deciding to leave the ocean for a totally alien place. Shear suspected that some sort of an ecological bridge might have been involved in making the transition, some environment that was not quite water and not quite land. And indeed, for billions of years, bacterial and algal mats had existed in the shallows along continental margins. Although this scum probably provided the perfect transitional environment, the first tiny land arthropods were found among primitive land plant fossils. To extract these minute fossils for study, Shear used hydrofluoric acid to dissolve the rock surrounding them, leaving only organic fragments containing the remains of both the plants and minute animals. “I can remember seeing some of the really striking fossils for the first time,” he recalls. “I got a feeling of excitement that’s probably very similar to scoring the big touch down at the Homecoming game. You just feel on top of the world, and it makes it worth all of the tedious searching and work that leads up to that.” After he succeeded in extracting the microfossils from the rock, Shear painstakingly pieced together the chips and scraps of these tiny animals and found a whole suite of arthropods, including a creature not unlike a modern spider. The rock could be dated, and the addition of that



Scientist, Bill Shear

clue meant that these microscopic spiders had made landfall at least 40 million years after the eurypterids' first brief excursion onto dry land. In separate but similar forays, the other branches of the arthropods probably launched themselves into the new world at different times.

And then what happened?

Since the invention of flight by insects probably allowed for their enormous diversification, I would say that it was one of the most important events in the history of the earth.

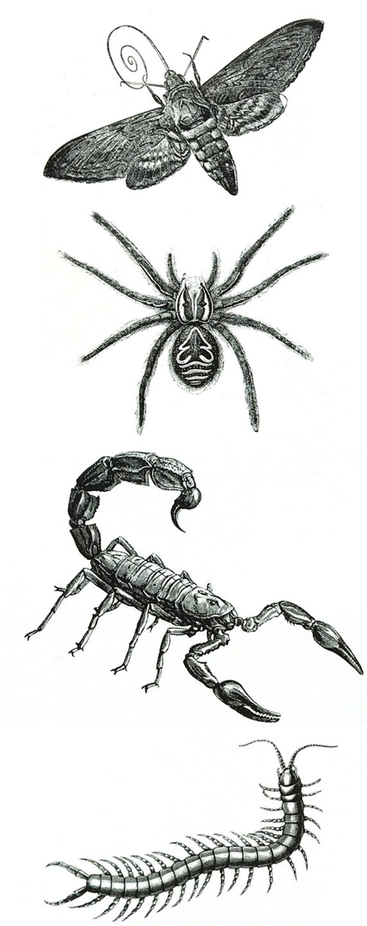
Bill Shear, Paleontologist

Arthropods took over the earth.

Fossil fragments are pieced together to reveal an early spider

First, with their highly adaptable body plans, they evolved a way to breathe air. In the damp coastal zone spiders modified their book gills to become book lungs, very similar biological devices.. When the insects showed up, their bodies solved the problem of breathing air with a tracheal system that essentially allows them to mainline oxygen directly into their muscles without passing it through any gill-like or lung-like structures. They could draw air into their bodies through minute pores on their undersides, near the junction of their appendages and their shells, and distribute it through their bodies in a kind of open capillary system. A concentrated supply of oxygen as a gas reaches every cell of the insect's body. This kind of internal plumbing makes insects and other arthropods intensely aerobic, feeding their muscles enormous doses of oxygen and allowing them to move very quickly. Eventually, some spiders and millipedes would evolve tracheal systems, too, an example of the dynamic parallel evolution of which arthropods are so capable.

Once the arthropods were air breathers, their dependence on damp coastal environments ended and they began to move inland. They fed on the rich detritus of organic plant debris, much in the same way that burrowing worms thrived on the debris sediments in the sea. Living plants provided limited potential for nourishment because their cells have hard walls that were difficult for the first waves of tiny bugs to penetrate. But the invading arthropods found plenty of debris broken down by fungi and bacteria that was much easier to digest. Naturally, with their ancient histories and skills as carnivorous predators, many of the first land-dwellers ate each other, dead or alive, and the same arms race that produced dramatic evolution in the ocean began on land.



Various arthropod groups: Insect; spider; scorpion; centipede.

Among their adaptive strategies, some arthropods evolved as hunters in fresh water, reverting to exclusively aquatic lives. Others came up with multiple developmental stages as predators in the water, on land, and in one of the great radiations in nature, in the air. Learning to fly was the tour de force of the insect branch of the arthropods, perhaps the single most important adaptation that allowed them to eventually dominate every habitable ecosystem on earth.

A damselfly emerges from its nymph stage after simple metamorphosis

The small size of insects, perhaps a drawback in the sea and certainly a problem for most other animals on land, gave them an advantage when trying to get into the air. They also got a boost from their highly adaptable appendages, which were able to create wings, probably from airfoil-like structures that evolved on their thoraxes and continued to evolve as the advantages of flight were passed from generation to generation.

Dragonflies are acrobatic predators of the sky

Arthropods' tracheal breathing systems, evolved during the colonization of dry land, also proved very efficient at oxygenating the fast-moving muscles necessary for flight. For the muscles in a bird to do the same work as a mosquito in flight, its lungs would be too big and heavy to allow flight at all. A large animal simply cannot contract its muscles at the same rate as an insect, and so depends on increasing the efficiency of its wings.

Insects began to fly soon after their ancestors first came ashore, and when they did, their dominance of land began in earnest. Flight gave them a speed advantage over other ground-bound insects and animals of all kinds that was simply insurmountable. The ground speed of a running insect, for instance, is about .2 miles per hour; for a flying insect, about 35 miles per hour.

A spider spins a web and waits

Once the air was alive with animals, it became a new food niche for animals that were able to capitalize on meals hurtling through the sky. Spiders. These ground-bound arthropods figured out how to catch flies, gnats, and their other airborne cousins in great nets spun across the sky. A spider web is one of the most marvelous structures on earth, spun in patterns that have delighted humans forever and strong enough, if proportionate in size, to stop a flying 747 airliner. Flight also was the greatest step in the weaving of an ecological tapestry upon which all animal life on earth now depends -- the synergy between flowering plants and insects.

Our Insect Partners

Arthropod statistics, past and present are staggering. Of the million or more described species of living animals, three-fourths of them are arthropods that together consume the greatest amounts and kinds of food on land and in the sea, and occupy the widest variety of habitats. Because of the entangled dependencies of all ecosystems, their success has also rendered most of the rest of the world's living things literally helpless without them. Most flowering plants, for instance, require insects for their survival, a biological collaboration of such importance that life as we know it would cease to exist without it. These two empires of plants and animals are intricately united with insects consuming every part of the plant, and most flowering plants dependent on the insects for pollination and reproduction. Also, plants owe bugs their lives because, like earthworms, insects turn the soil around their roots and decompose dead tissue into the nutrients for growth.

A vast majority of people consider it a high priority to minimize the extent of their interaction with the insect world. . . .But because insects are in many cases the chief architects of terrestrial ecosystems, they are also our principal partners in making a living on earth. Without insects, there would be no oranges in Florida, no cotton in Mississippi, no cheese in Wisconsin, no peaches in Georgia and no potatoes in Idaho.

May R. Berenbaum, Entomologist
Bugs in the System: Insects and Their Impact on Human Affairs

Flying insects carry pollen from flower to flower

Insects and other land-dwelling modern arthropods are so important that if all were to disappear, humanity could not last more than a few months and most of the other mammals, amphibians, and birds would crash to extinction at the same time. Without arthropods, the terrestrial surface would simply rot. Dead vegetation would pile up and dry out, closing the nutrient cycles and forcing the end of living plants. As the earth adjusted itself to this new ecological formula without insects, funguses would explode into the unoccupied niches, but soon, they too would disappear as their own nutrient cycle dependent on organic debris ceased to function. The continents of earth would return to about the same condition they were in before animals made landfall, covered by mats of bacteria and primitive plants.

Eventually, though, the arthropods might invade again to reclaim the land.

From top clockwise: fly drinking nectar; sow bug; bee pollinating; ceanothus silk moth on cocoon.