Shape of Life

Getting A Head

The First Hunter

When you collect marine animals there are certain flatworms so delicate that they are almost impossible to capture whole, for they break and tatter under the touch. You must let them ooze and crawl of their own will onto a knife blade and then lift them gently into your bottle of seawater.

JOHN STEINBECK, CANNERY ROW

And now, the news ...

Flatworms Attack 200 Million People

(Geneva, Switzerland) *The World Health Organization reports that more than 200,000 people worldwide are carrying deadly parasitic flatworms and that over one-sixth of the world's population is at risk in seventy-four countries. The resulting disease kills up to 20,000 people a year and leaves other victims in a state of chronic ill health. It's known as intestinal schistomosiasis, and is caused by the tiny* Schistosoma mansoni *flatworm, also known as a blood worm. It has no known cure.*

Schistosomiasis has been recognized since the time of the Egyptian pharaohs, and the worms that cause it were first discovered in 1851 in Cairo by a young German pathologist, Thodor Bilharz. The disease is also called Bilharziasis, in his honor.

Thirty-Seven-Foot Tapeworm Sets Record

(Great Grits, Mississippi) *On September 5, 1991, doctors extracted thirty-seven continuous feet of tapeworm from Sally Mae Wallace of Great Grits, Mississippi, setting a new record for the United States. Tapeworms are segmented flatworms, which attach themselves to the intestines of their hosts. The chief symptom of tapeworm infestation is weight loss, and tapeworm eggs have been capsuled and sold as a diet pill. When the desired amount of weight had been lost, you take another pill to kill the tapeworm. The largest tapeworm ever found measured over 230 feet in length and had over 11,000 segments, or over 22,000 individual sexual organs.*

"After about twenty feet of that thing had come out," Sally said, "I just knew I had the record. I was really filled with joy."

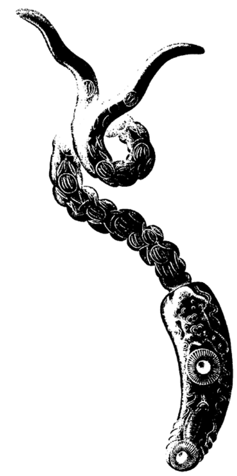
Carnivorous Worms Roam Wild in the UK

(Dunoon, Scotland) *An invasion of alien predators in the Scottish Highlands is threatening to destroy thousands of acres of farms that are home to sheep, cattle and people. New Zealand flatworms, voracious carnivores believed to have arrived as stowaways in potted plants, are eating up the earthworms upon which the highland fields and meadows depend for aeration, drainage, and fertilization. Now, many of the fields are becoming swampy and useless for grazing or planting. Researchers say there is evidence that the flatworm invasion is spreading throughout the United Kingdom.*

A New Zealand flatworm attacking an earthworm

"The first time I remember being aware of them was when fishermen came here a few years ago to look for worms for fishing and they complained there were no earthworms," said farmer Tom Hills. "So then they started to look for reasons why there were no earthworms and they come up with the flatworm."

"They're alien," said Mr. Hill's wife. "And they're quite sinister, really. And underneath the ground, you can't see them. But they're devouring earthworms."



According to Hugh Jones of the National Flatworm Survey, a couple of dozen flatworms in a single field can eat a thousand earthworms a year. "Initially, they were just regarded as a curiosity, another one of these imported animals that probably doesn't do much harm. Turned out these things are carnivores, they're hunting other animals."

Ancient Worms

Over the millions of years that animals have been living on earth, they have learned to exploit every available source of food and to do that, many have become hunters of other animals. At some point in the distant past, the first animals capable of actively hunting showed up with bodies suited for the job, and lions, tigers, sharks, people and all the rest of the world's hunters inherited their tools. The earthworm predators of Scotland, giant tapeworms in Mississippi, and parasitic flatworms that wreck hundreds of thousands of human lives are the descendants of those first hunters that have carried their body architecture into the present. They don't make very good company, but they have a heck of a story to tell.

To hear that story, though, we have to listen very carefully, because the first hunters barely whisper to us from their beginnings over half-a-billion years ago. And we need translators who understand the languages of the past that resonate in fossils of ancient animals, more recently, in the genetic code, another tracing carried in all living things. One of those translators, James "Whitey "Hagadorn, is a paleontologist - literally 'one who knows of past times.' He likes the outdoors, spent a lot of time at a university learning the languages of the past, and now burns with curiosity about his particular passion, ancient worms. "I'm playing detective in deep time," he says. "I mean, I'm trying to think what was on the sea floor 565 million years ago."

A fossil is any evidence of ancient life – usually bones, teeth, shells, tissue, tracks, or traces – that remained buried and undisturbed in sediment that became rock. Becoming a fossil, though, isn't just a matter of dying and laying around for millions of years. When most animals die, they get eaten or just rot in a process that depends on oxygen to break down their body chemistry into carbon and other elements, leaving behind hard bone, teeth or shells. If these hard parts get buried by sediment that turns to rock, they become fossils.

James Hagadorn examining a fossil bed in the White Mountains

On rare occasions when an animal dies and is quickly covered up by sediment or ash, the oxygen can't get to their bodies and then the eons of pressure transforms its entire body into a fossil. It's the exquisite details of anatomy left by these soft-body fossils that often provide major breakthroughs in the study of paleontology. Only in rare cases have sponges, cnidarians, and flatworms spoken to us from deep time through their fossils. Their bodies were made of water, jelly, collagen and other goo that doesn't turn to rock like the bones, shells, and other hard parts of bugs, fish, dinosaurs and other animals. Still, paleontologists have found fragile traces of worms and other soft-bodied animals, and have discovered spectacular evidence of their presence -- their tracks.

Sponges don't get around much, and even though jellyfish, anemones and the other cnidarians had muscles and nervous systems, they couldn't go out and pursue prey. The earliest hunters, though, threw a new wrinkle into the business of living and our ability, now, to interpret their presence on earth: They moved around and left trails. "The trick that we have as paleontologists," says Whitey Hagadorn, "is to go back in the geologic record and look in the rocks for evidence of tracks or trails of ancient organisms, particularly for intervals of time when maybe the animals themselves aren't preserved. In a way, an animal's tracks record its movement, its behavior, its size, writing its steps in the earth."

Trace Fossils Tell a Story

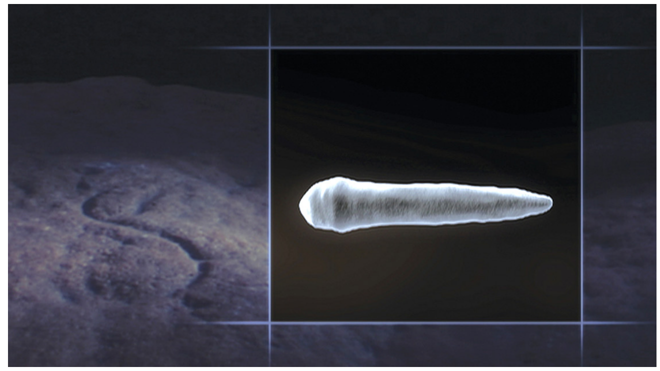
Fossils turn up in the darndest places.

Niles Eldridge Life Pulse, Episodes from the Story of the Fossil Record

In the Inyo Mountains of California, among many other places in the world, Hagadorn found the tracks of some of the earliest creatures that moved around and died in just the right way to leave the evidence. The traces look like the remains of an angel hair pasta lunch that had been wrapped in newspaper, thin impressions of sinuous strands of something that left micro-trenches in the surface of the rock strata. "I get a clue here, a clue there, and I try to piece them together and create a story to find out who the culprit was. Right about this time, about 565 million years ago," Hagadorn says of those rocks that are now part of California, "there was sort of a revolution in animal body plans. Organisms for the first time became able to move on their own accord in a directed fashion. We know this because we can look at their trace fossils. By looking at this trail, we can certainly say that whatever made it had the ability to move sediment. Prior to this time, there weren't many things that could do that."

The question is: what kind of animal was it?

There are many clues in Hagadorn's tracks in the rocks that sketch a portrait of the animals that left them. The trackways are only a few millimeters wide, so the animals had to be thin. The track is rounded, so the creature was probably cylindrical, and there are no scratches along the edge of the trail so it is very unlikely that the animal had arms, legs or any other appendages. In short, we're talking about a worm, but one other thing about the trackway hints at a revolution in the body plan of animals. The trail shows evidence of a sense of direction. The animal was going *somewhere* and not just drifting in the water. These whispers from deep time carry a profound message: This animal had a head and knew where it was going.



Early fossilized track and the hypothetical animal that made it

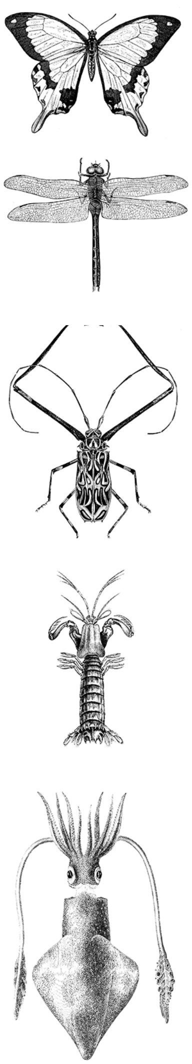
A New Body Plan

If you ask most people to name five animals, most likely you'll get a list something like, "cat, dog, fish, horse, and bird," or perhaps from those who think they are being really insightful, human. All of those familiar creatures are indeed animals, and all share the same body plan that includes a head, as do worms, insects, and most other things we call animals. So what's the big deal about finding the 565 million-year-old trail of a creature with a head?

Orientation directly towards a goal can be achieved only in three ways. Either the sense organs must themselves be directional . . . or the animal must compare the signals from pairs of similar sense organs on two sides of the body . . . or the animal must be able to compare signals in time.

Martin Wells,
Lower Animals

For starters, something had to come first. And that animal pioneered a way of living that depended upon mobility and hunting, which required a head that contained sense organs of some kind so it would know where it was going. This breakthrough in design was enormous, and gave those creatures with heads a huge advantage over animals that could only sit and wait for food to float to them, or pulse aimlessly through the water in search of a meal. As soon as animals with heads appeared in the sea, they became the dominant form of life on earth. Imagine your feet being glued to the sidewalk while large, stalking cats patrol your neighborhood looking for a nosh. In the coming eons, animals as small as flies and as large as elephants would evolve using the same basic architecture and strategies for survival as the earliest flatworms.



Most familiar animals have a head and are bilateral

The trackways and the bodies of the creatures that left them also reveal another masterpiece of body architecture: They were bilateral. That means that their two sides mirrored each other, and because they had heads, they also had tails. Just like us. We take this basic formula for building an animal body for granted, but the Neil Armstrongs of heads and bilateral symmetry first left their footprints in the earth way back when those rocks began their journey into the present, carrying their messages from the distant past.

The First Hunter

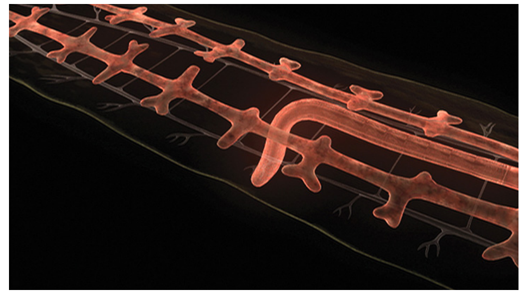
We may never know for sure which specific animal was the very first hunter with a head and all the other equipment for leading that revolution. From the clues in the rocks, we do know it was a creature much like those killer worms of Scotland, or tapeworms, and other nasty parasites. About 20,000 kinds of flatworms still make a living with the same primitive body plan that showed up so long ago, alive and well in fresh and salt water, and other nice damp niches. Their name, *Platyhelminthes,* (Plat-y-hel-min-thies) comes from the Greek and means, simply, flatworm.

It takes more than a lively imagination to identify with an ameba, which has no fixed front or rear, or with a medusa, which has multiple eyes encircling an umbrella-shaped body. . . Now, we come at last to some invertebrates in which it is easy to tell head from tail, back from belly, and right side from left.

Vicki Pearse, John Pearse, Mildred Buchsbaum, Ralph Buchsbaum, Living Invertebrates

Modern flatworms' thin bodies have complex organs

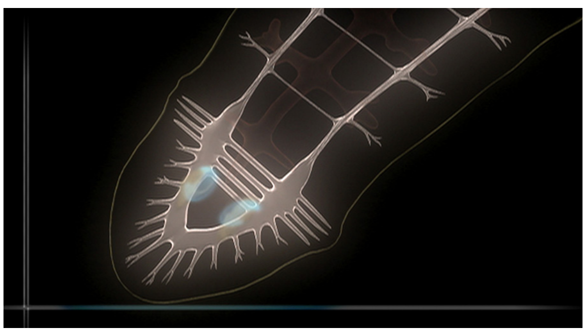
Like their ancient cousins, modern flatworms are soft-bodied, ribbon-shaped animals made of tissue that is further organized into systems of organs. Their bodies have no real central cavity, but rather a layer of tissue in which their organs, nerves, and sensors are embedded in separate pockets. Their bodies have only a single opening, which serves as both a waste disposal and a mouth, though many flatworms eat by extending a tube called a pharynx out of the opening and into their prey. The lining of the pharynx secretes enzymes, which soften the bits of food that the muscles of the pharynx then pass into the flatworm's body. A flatworm passes its meal through its body in a gut that is not a central channel but more of a network of branches that distributes the food directly to the rest of the body. The system also works in reverse to get rid of waste.



A planarian's pharynx and branching gut

The pharynx extended and feeding

A New Nervous System

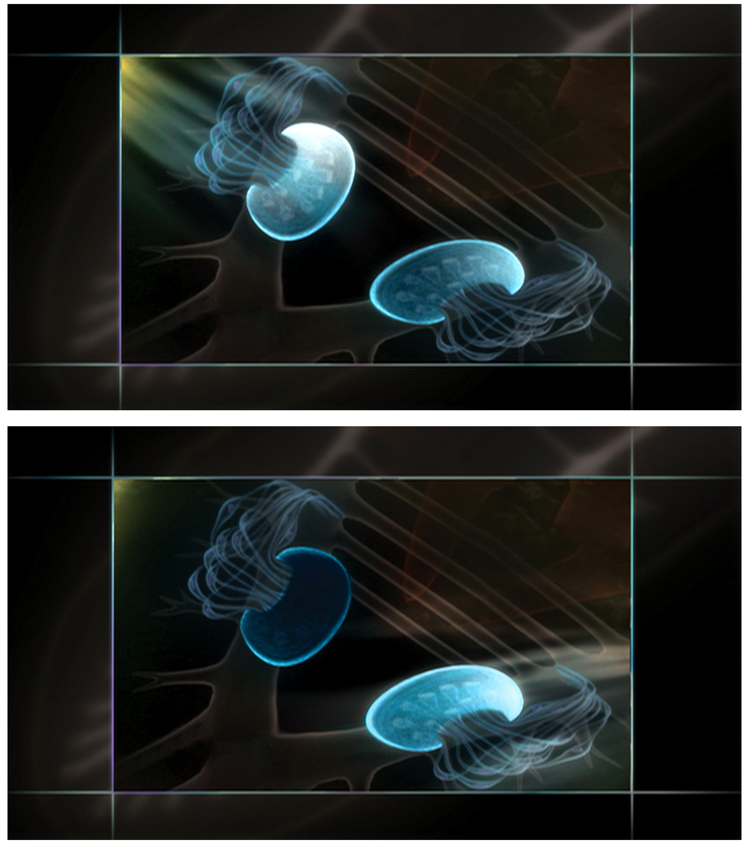


Nerves in the head form a simple brain

An ancient flatworm was also the first creature to have a brain—a bundle of nerves to which nerve impulses are transmitted from sensors such as eyes, and smell and taste receptors so the animal knows where it is, where its food is, and where its enemy is. The brain interprets the signals from the sensors and the flatworm can adjust its course, speed up, or slow down. This whole set up is called a central nervous system and is very big news on the evolutionary front, since all things we call animals that were around before flatworms were much less complex. And they were much less capable of moving around and hunting for food.

The combination of bilateral symmetry and a central nervous system is very logical and works like this. Free-living flatworms (many are parasitic and just ride along in a host) use their network of sensors to detect food, chemicals that lead them to prey or away from predators, objects that can stop their progress, or even water currents. These sensors are paired and placed on opposite sides of their bodies, so the worm can compare the relative nearness, distance, or strength of the sensory input. Two light receptors that are really primitive eyes give them stereo sight. Their eyes are tiny bowls lined with specialized sensory cells containing black pigment, each of which ends in a nerve fiber connected to the brain. When light hits the dark pigment within one of those cells, it causes a chemical reaction that triggers the nerve fiber to send a signal to the brain.

These primitive eyes tell the direction of the light by which cup receives a stimulus and exactly which part of the pigment cup receives the stimulus. If the light is entirely from the right side, only the right cup gets stimulated because the left cup is shaded. If the light is exactly in front, both sides get stimulated in the same part of the cup. If the worm wants to go toward the light, it turns until the same spot in each cup is stimulated by the light. This will mean that the light is directly ahead. While most of these light-sensing cells are clustered in the pair of eyes, some are scattered in different – but bilaterally equal – locations around the body. The other types of sensors for smell, touch and taste, are also paired. A flatworm becomes more sensitive – and quicker to react – as it gets closer to the source of the stimulus because its relative intensity becomes much more apparent to two receptors spaced only a flatworm's-width apart.

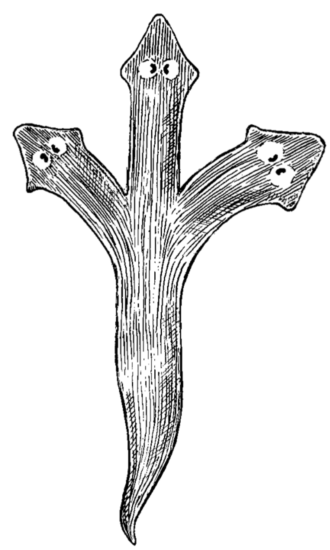


Stereo eyes sense direction of light

An Excellent Defense: Regeneration

Flatworms have been trained to run mazes according to light cues and remember where and in which direction to turn or go straight after a few tries, a stupid pet trick that has never appeared on televisions but probably should. And for an encore, the host/hostess can cut one flatworm that has learned to run the maze into two, each half will grow a new head or tail depending on which it needs, and both will be able to run the same maze from memory. This *tour de force* of animal life is called regeneration.

All animals can regenerate their tissues to some degree, but flatworms are grand champions. We humans and other mammals do it, of course, when we slough off millions of skin cells every day and replace them with new ones. We can also grow new skin, nerves, and blood vessels to cover a wound, or knit our bones together after a break. Other animals can replace arms, legs, and tails, but the general rule is that the more complex an animal is, the less its capacity to regenerate its body parts. Sponges and cnidarians do a pretty good job with regeneration, and can grow whole new animals from tiny flakes or buds of themselves. But their bodies are much simpler collections of cooperating cells than those of flatworms. What makes the regenerative ability of flatworms so interesting and remarkable is that their bodies feature the earliest hints of true animal complexity – brains, organs, a nervous system, heads, and tails. They look like animals, and their regenerative repertoire can be startling. Almost every biology student has seen or heard of a multi-head monster *planaria* flatworm made by making many cuts in its head and allowing each to regenerate into a whole new one.

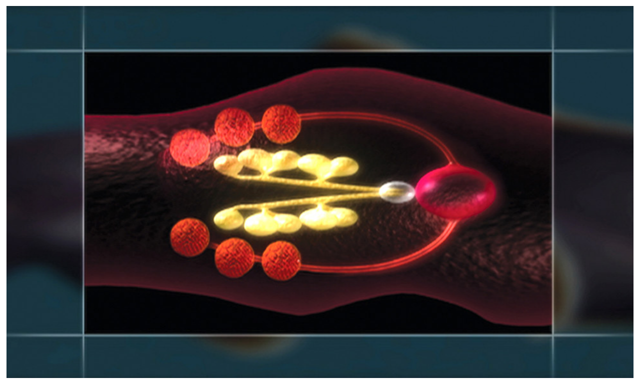


A multiheaded planarian

Flatworms, like the ones terrorizing earthworms in the muck of Scottish farms, are as effective as lions chasing down gazelles, and because they can regenerate so efficiently, they are very hard to kill. "How do you kill them?" asks one of the members of the anti-flatworm squad in the Highlands. "I have absolutely no idea because you find them under the stones or rocks and they're just flat. And you stand on them, you jump on them, makes no difference. They don't go away. What can you do? Pulverize them? Turn them into mush?"

The regeneration cells are called *neoblasts,* which just means 'cells of newness'. When a flatworm is wounded or cut in pieces, these special cells immediately begin to migrate toward the site of the damage. The movement of the neoblasts is either triggered by the release of some chemical from the wound, or by some impulse transmitted in the nervous system, or both. Once the neoblasts get to the site, they contain the genetic information to produce any or all of the necessary cells to make the animal whole again.

Both Female and Male



Flatworms have both male and female sex organs

Obviously, replicating oneself through regeneration is a form of reproduction, and some flatworms depend heavily on it for keeping the generational train on the track. Most, though, are pure sex machines with both male and female organs and twice the chance of getting a date when the time for reproduction rolls around. A typical flatworm, say a half-inch long, common little number called a planarian, has a pair of ovaries set right behind its eye buds, and the ovaries secrete eggs through oviducts to a system of yolk glands that are strung out along each side of its body. The planarian also has a whole series of testes connected by ducts set at intervals along two channels that run from head to tail. Every flatworm has a penis, or several, and one or more genital pores for receiving the unique, two-tailed sperm produced during copulation.

A penis-fencing flatworm jabs its partner (top) and leaves a trail of white sperm (bottom)

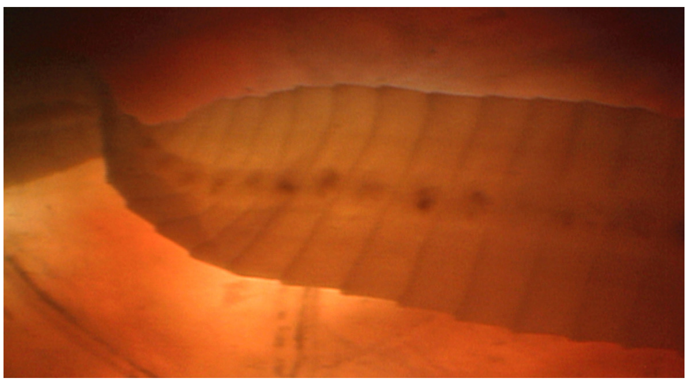
You'd think that with that kind of sexual plumbing, a flatworm would never have to leave the house to mate, but most do not self-fertilize. Instead, a flatworm only has to find another flatworm — any other flatworm of the same species — and actually come together so their lower, or ventral surfaces touch. Mating looks more like a fight than romance, with each flatworm trying to get its penis into the genital pore or even just the skin of the other. When any puncture leads to pregnancy, flatworm penis-fencing is mortal business. And the first to succeed becomes the de facto male, the other the female. In a sense, mating is a fight because the worm that becomes the female then has to expend considerable energy growing and caring for the newly fertilized eggs. For free-living flatworms, though, like the planarians and those in the seas, ponds, or swamps, being hermaphroditic is a very good reproductive strategy since the odds for success are doubled.

The Parasite Way of Life

The most common kind of relationship between one animal and another, or between an animal and a plant, is that of diner and dinner.

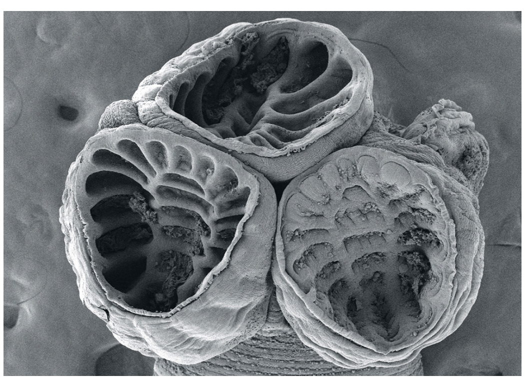
Vicki Pearse, John Pearse, Mildred Buchsbaum, Ralph Buchsbaum, Living Invertebrates

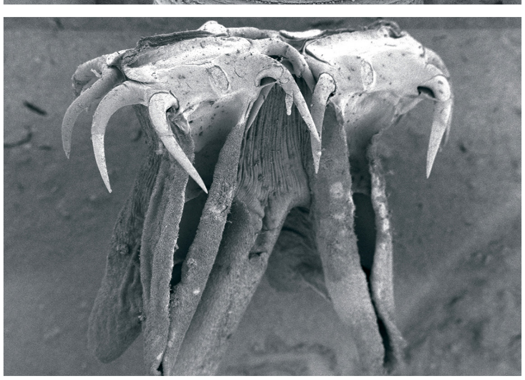
The earliest flatworms were free-swimming, free-living creatures that became the earth's first hunters and went on to over half-a-billion years of success. Modern flatworms, including the turbellarians and planarians, look a lot like them. Others, like Sally Wallace's record-breaking tapeworm, have taken a different evolutionary trajectory and adapted their basic body plan and behavior over millions of years to become parasites. Their survival depends upon a lifestyle that helps them find and exploit a host, but their goals remain the same as those of every other member of the kingdom: Stay alive. Eat. Make more animals like themselves.



A tapeworm is a string of reproductive segments

Sally's tapeworm, and others like it, take their nourishment at a considerable cost to their hosts (remember the diet pill worms) and also depend on themselves and the conditions in the hosts for reproduction. And tapeworms aren't the only flatworms that have adapted the same basic body plan to ride along with other animals as parasites. Liver flukes, trematodes, and blood flukes like the schistosomes that cause Bilharziasis and kill 20,000 humans a year, are all variations on the same design. All have developed perfect strategies for getting into their hosts, feeding, and reproducing, sometimes moving between different kinds of animals at different stages of their development, from egg to adult, often in an endless circle. One of these, the broad fish tapeworm, typically lives in a large mammal like a bear, leaves that host as a fertilized egg in the bear's feces, settles into a stream bed or shore sand and protects itself for the time being by hardening its exterior into a kind of a shell. Then it's eaten by a minute crustacean called a copepod, which, in turn, is eaten by a salmon or other carnivorous fish, which is then eaten by another bear. And on, and on, and on. Through each stage, the tapeworm egg, larva and finally the adult, are perfectly suited for survival in the intermediate hosts.





The head of tapeworms are modified for attachment

Genes Over Evolutionary Time

All of our inquiry into the lives of ancient flatworms is really an epic investigation into our own origins and body plan, a lens into deep time that is now showing us a picture of genetic evolution. Until recently, our information about the connections of ourselves and other animals to the first flatworm hunters of the ancient past came from paleontologists like James "Whitey" Hagadorn and his trackways in the rocks, and from analyzing the relationships of anatomy and chemistry among modern animals. Halfway through the last century, though, we got our first real glimpse of life's grandest engine of inheritance, deoxyribonucleic acid – DNA. Since then, a patient investigation into these instructions for life, called the genetic code, has occupied the careers of thousands of scientists, including geneticist Matt Scott.

> *Genes survive down the ages only if they are good at building bodies that are good at living and reproducing in the particular way of life chosen by the species.*
>
> Richard Dawkins
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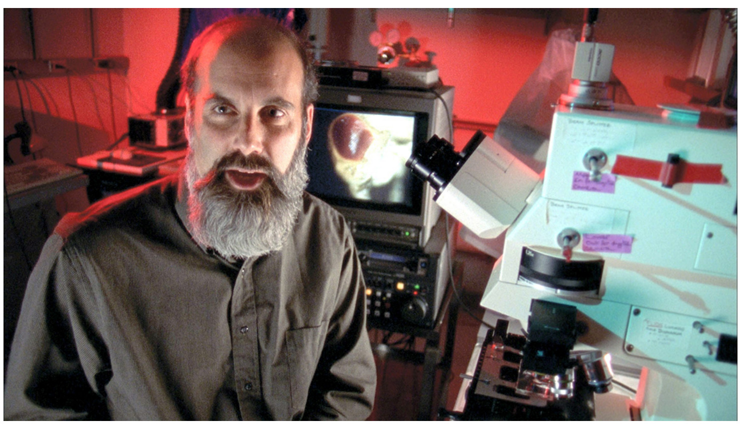
> River Out of Eden, A Darwinian View of Life

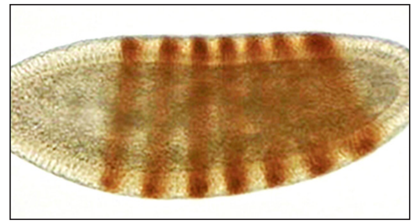


Matt Scott

While Hagadorn has been deciphering the external trails and traces of ancient life, geneticists like Matt Scott have been sorting through the mysteries of DNA trying to fathom the process by which animals create their own bodies. "All the cells in our body, with a few exceptions have a complete set of genes. And in those genes, in that fantastically complex and mysterious genome, are the instructions for building an organism," he says, reveling in the magnitude of his quest.

The genetic code within every living cell of an animal contains not only the instructions for building that animal, but within those instructions there is a record of the similarities shared by that animal with all of its ancestors. Think of that. If there was a first hunter with a bilateral body plan, it must have carried a set of genetic rules for making that kind of body. And if all bilateral animals are descendants of that animal, all those kinds of animals must share those same rules. In other words, all bilateral animals must have inherited that same set of rules for making the same kind of body. The genetic code that spelled 'bilateral animal' over half-a-billion years ago can still be read today in all living animals that have heads, tails and two sides that mirror each other. By comparing the genetic code of living animals, we know now that we have a lot more in common with an animal like Sally Wallace's tapeworm than is obvious at first glance.

To sort out the rules for making a bilateral body, Matt Scott looks at how the body of an animal is made when it grows from an egg to an adult. He has learned that the cells in a developing animal are told when, where and how to grow by obeying signals from special regulatory genes within the DNA molecule. These genes trigger the activity of other genes, controlling when and where they, in turn, are allowed to do their job of growing an eye, or any other particular part of the body. In this way, a special group of these regulators called Hox genes set up the head to tail axis of a bilateral body. It's like laying out a grid work pattern to be filled in with other instructions to eventually create an entire body plan.

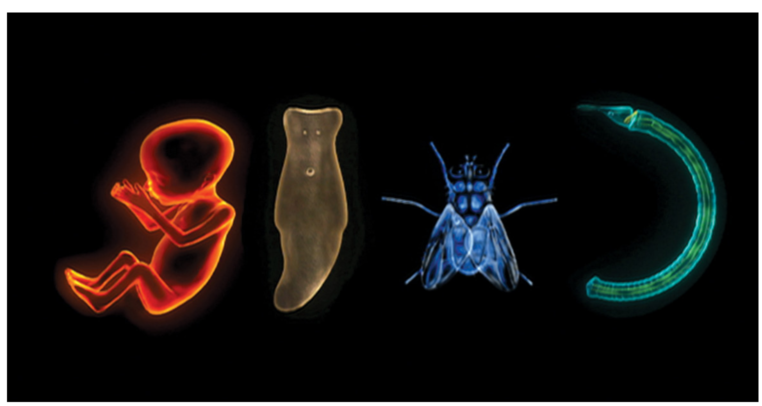


Fruitfly embryo

Regulation of the development of an animal is a bit like a set of signals that can switch themselves on or off to tell the individual genes in the massive sequence of instructions when to go into action. "Understanding how these genes build those patterns is a dream come true for a lot of biologists," says Matt Scott. In effect, to control the regulatory process of building an animal body, Hox genes are conducting an orchestra of thousands of other genes.

Making the dream come true has been a long and painstaking process of figuring out how genes create bodies by isolating the individual gene codes and looking at mistakes in the developmental process, called mutations, to figure out how they happened. In their labs, pioneer geneticists worked with tiny fruit flies because they are easy to raise by the millions and they reproduce fast to create generation upon generation of flies within a few weeks. By tinkering with their genetic codes, the geneticists created flies with legs growing out of their heads instead of antennae, or antennae growing where legs would usually be. They found out that in such mutant flies, it is the Hox gene that contains the mistake. The mutant gene produced its signal to produce a body part but in the wrong place.

This is not just a Mel Brooks Frankenstein movie with a fruit fly playing the role of the monster. By creating such mutations, the geneticists learned what the proper sequence should be to produce a leg in a leg's place, and which genes regulate events to produce that conclusion. It's just like breaking a code by trial and error. And by finding and comparing the Hox genes in lots of different animals, geneticists have found that those genes are very similar in all of them. Some Hox genes can actually be planted in totally different kinds of animals and still produce control signals for the very different kinds of body parts. A Hox gene that regulates the formation of an eye in a fruit fly, for instance, has been transplanted into a mouse to trigger the proper mouse sequence to create a proper mouse eye in the proper place. Only the genes native to a particular kind of animal, a mouse eye gene, can produce the end result, or a mouse eye, even though a Hox gene cracked the genetic whip.

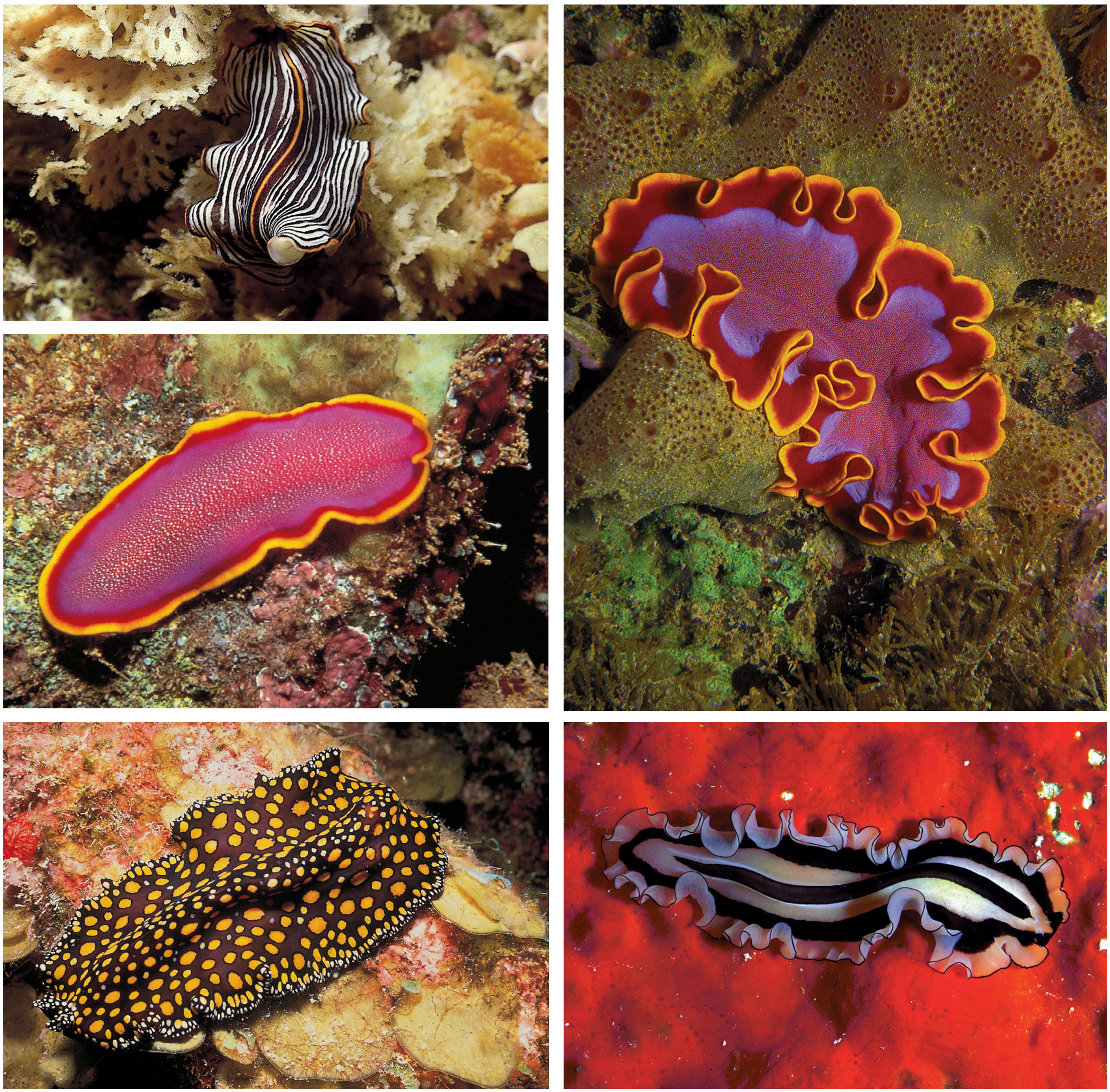


Hox genes direct body formation in all bilateral animals

This was an incredible discovery. It means that a fruit fly and a mouse – an insect and a mammal – have Hox genes that are so similar they can be interchanged. And even more incredibly, when biogeneticists looked at Hox genes from all kinds of other bilateral animals, they found that their codes were amazingly similar. The Hox genes in different animals did not produce the same body plan in all of them, but they laid out a similar pattern in all bilateral animals. The startling conclusion: Even though insects and mammals have very different body plans, they must share a common ancestor whose DNA contained the first Hox genes.

That ancestor, therefore, must have been the first bilateral animal, which gets us back to Hagadorn's version of time travel. He and other paleontologists have fixed the time that the earliest tracks of bilateral animals appear on earth, left there by a primitive version of a modern flatworm. By combining those discoveries with the story of the Hox gene's voyage through time, we know that those ancient flatworm-like creatures pioneered the basic body plan which has been inherited by us and all other animals with heads, tails and places to go.

Before we give Tom Hills the news that it's his own relatives tearing up his farm in Scotland, we'd probably better take him down to the pub for an ale or two.



Many modern flatworms have colorful bodies with striking designs, but it's not clear why.