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Do Parasites Rule the World?

New research shows that parasites not only control the behavior of their hosts, they can change entire ecosystems to suit their needs

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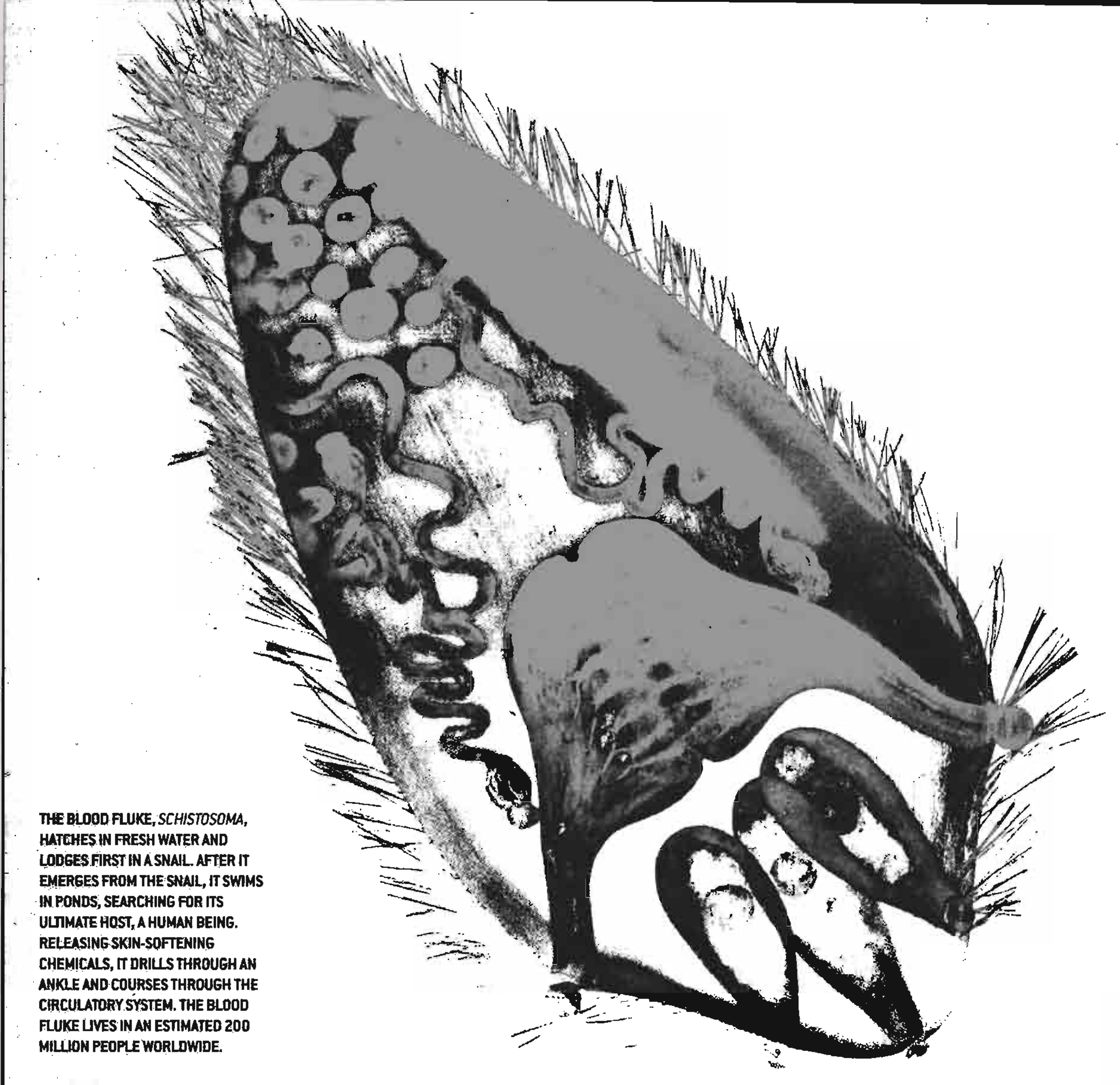
Do Parasites Rule the World?

NEW EVIDENCE INDICATES OUR IDEA OF HOW NATURE REALLY WORKS COULD BE WRONG

BY CARL ZIMMER

OPPOSITE: THE HOOKWORM, WHICH INFECTS 1.3 BILLION PEOPLE WORLDWIDE, SINKS ITS TEETH INTO THE HOST'S INTESTINAL WALL AND SUCKS BLOOD FROM THE WOUND. THIS PAGE: A PARASITIC CRUSTACEAN ANCHORS ITSELF WITH ITS LEGS INTO THE EYE JELLY OF ITS HOST, A GREENLAND SHARK.



THE BLOOD FLUKE, *SCHISTOSOMA*, HATCHES IN FRESH WATER AND LODGES FIRST IN A SNAIL. AFTER IT EMERGES FROM THE SNAIL, IT SWIMS IN PONDS, SEARCHING FOR ITS ULTIMATE HOST, A HUMAN BEING. RELEASING SKIN-SOFTENING CHEMICALS, IT DRILLS THROUGH AN ANKLE AND COURSES THROUGH THE CIRCULATORY SYSTEM. THE BLOOD FLUKE LIVES IN AN ESTIMATED 200 MILLION PEOPLE WORLDWIDE.

ON A CLEAR SUMMER DAY ON THE CALIFORNIA COAST, THE CARPINTERIA salt marsh vibrates with life. Along the banks of the 120-acre preserve, 80 miles northwest of Los Angeles, thousands of horn snails, their conical shells looking like miniature party hats, graze the algae. Arrow gobies slip through the water, while killifish dart around, every now and then turning to expose the brilliant glint of their bellies. Fiddler crabs slowly crawl out of fist-size holes and salute the new day with their giant claws, while their bigger cousins—lined-shore crabs—crack open snails as if they were walnuts. Meanwhile, a carnival of birds—Caspian terns, willet, plover, yellowleg sandpipers, curlews, and dowitchers—feast on littleneck clams and other prey burrowed in the marsh bottom.

Standing on a promontory, Kevin Lafferty, a marine biologist at the University of California at Santa Barbara, watches the teeming scene and sees another, more compelling drama. For him, the real drama of the marsh lies beneath the surface in the life of its invisible inhabitants: the parasites. A curlew grabs a clam from its hole. "Just got infected," Lafferty says. He looks at the bank of snails. "More than 40 percent of these snails are infected," he pronounces. "They're really just parasites in disguise." He points to the snowy constellation of bird droppings along the bank. "There are boxcars of parasite biomass here; those are just packages of fluke eggs."

Every living thing has at least one parasite that lives inside or on it, and many, including humans, have far more. Leopard frogs may harbor a dozen species of parasites, including nematodes in their ears, filarial worms in their veins, and flukes in their kidneys, bladders, and intestines. One species of Mexican parrot carries 30 different species of mites on its feathers alone. Often the parasites themselves have parasites, and some of those parasites have parasites of their own. Scientists have no idea of the exact number of species of parasites, but they do know one fact: Parasites make up the majority of species on Earth. Parasites can take the form of animals, including insects, flatworms, and crustaceans, as well as protozoa, fungi, plants, and viruses and bacteria. By one estimate, parasites may outnumber free-living species four to one. Indeed, the study of life is, for the most part, parasitology.

Most of the past century's research on parasites has gone into trying to fight the ones that cause devastating illness in humans, such as malaria, AIDS, and tuberculosis. But otherwise, parasites have largely been neglected. Scientists have treated them with indifference, even contempt, viewing them as essentially hitchhikers on life's road. But recent research reveals that parasites are remarkably sophisticated and tenacious and may be as important to ecosystems as the predators at the top of the food chain. Some castrate their hosts and take over their minds. Others completely shut down the immune systems of their hosts. Some scientists now think parasites have been a dominant force, perhaps *the* dominant force, in the evolution of life.

***SACCULINA CARCINI*, A BARNACLE THAT MORPHS INTO PLANTLIKE ROOTS,** is not the kind of organism that commands immediate respect. Indeed, at first glance *Sacculina* appears to slide down the ladder of evolution during its brief lifetime. Biologists are just beginning to realize that this backward-looking creature is a powerhouse in disguise.

Sacculina starts life as a free-swimming larva. Through a microscope, the tiny crustacean looks like a teardrop equipped with fluttering legs and a pair of dark eyespots. Nineteenth-century biologists thought *Sacculina* was a hermaphrodite, but in fact it comes in two sexes. The female larva is the first to colonize its host, the crab. Sense organs on the female *Sacculina*'s legs catch the scent of a crab, and she dances through the water until she lands on its armor. She crawls along an arm as the crab twitches in irritation—or perhaps the crustacean equivalent of panic—until she comes to a joint on the arm where the hard exoskeleton bends at a soft chink. There she looks for the small hairs that sprout out of the crab's arm, each anchored in its own hole. She jabs a long hollow dagger through one of the holes, and through it squirts a blob made up of a few cells. The injection, which takes only a few seconds, is a variation on the molting that crustaceans and insects go through in order to grow. For example, a cicada sitting in a tree separates a thin outer husk from the rest of its body and then pushes its way out of the shell, emerging with a new, soft exoskeleton that stretches throughout the insect's growth spurt. In the case of the female *Sacculina*, however, most of her body becomes the husk that is left behind. The part that lives on looks less like a barnacle than like a microscopic slug.

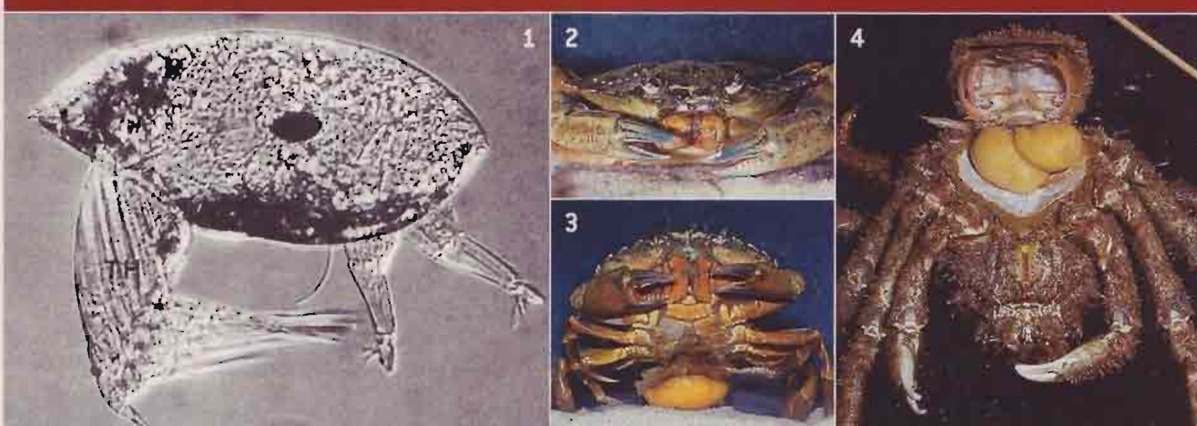
The slug plunges into the depth of the crab. In time it settles in the crab's underside and grows, forming a bulge in its shell and sprouting a set of rootlike tendrils, which spread throughout the crab's body, even wrapping around its eyestalks. Covered with fine, fleshy fingers much like the ones lining the human intestine, these roots draw in nutrients dissolved in the crab's blood. Remarkably, this gross invasion fails to trigger any immune response in the crab, which continues to wander through the surf, eating clams and mussels.

Meanwhile, the female *Sacculina* continues to grow, and the bulge in the crab's underside turns into a knob. As the crab scuttles around, the knob's outer layer slowly chips away, revealing a portal. *Sacculina* will remain at this stage for the rest of her life, unless a male larva lands on the crab and finds the knob's pin-size opening. It's too small for him to fit into, and so, like the female before him, he molts off most of himself, injecting the vestige into the hole. This male cargo—a spiny, reddish-brown torpedo 1/100,000 inch long—slips into a pulsing, throbbing canal, which carries him deep into the female's body. He casts off his spiny coat as he goes and in 10 hours ends up at the bottom of the canal. There he fuses to the female's visceral sac and begins making sperm. There are two of these wells in each female *Sacculina*, and she typically carries two males with her for her entire life. They endlessly fertilize her eggs, and every few weeks she produces thousands of new *Sacculina* larvae.

Eventually, the crab begins to change into a new sort of creature, one that exists to serve the parasite. It can no longer do the things that would get in the way of *Sacculina*'s growth. It stops molting and growing, which would funnel away energy from the parasite. Crabs can typically escape from predators by severing a claw and regrowing it later on. Crabs carrying *Sacculina* can lose a claw, but they can't grow a new one in its place. And while other crabs mate and produce new generations, parasitized crabs simply go on eating and eating. They have been spayed by the parasite.

Despite having been castrated, the crab doesn't lose its urge to nurture. It simply directs its affection toward the parasite. A healthy female crab carries her fertilized eggs in a brood pouch on her underside, and as her eggs mature she carefully grooms the pouch, scraping away algae and fungi. When the crab larvae hatch and need to escape, their mother finds a high rock on which to stand, then bobs up and down to release them from the pouch into the ocean current, waving her claws to stir up more flow. The knob that *Sacculina* forms sits exactly where the crab's brood pouch would be, and the crab treats the parasite knob as such. She strokes it clean as the larvae grow, and when they are ready to emerge she forces them out in pulses, shooting out heavy clouds of parasites. As they spray out from her body, she waves

THE MICROSCOPIC CRUSTACEAN *SACCULINA* (1) CONVERTS ITS CRAB HOST (2) INTO A CASTRATED, MINDLESS SLAVE. AN INVADING FEMALE PARASITE FIRST COLONIZES THE CRAB, THEN BIDES HER TIME UNTIL A MALE OR TWO COME ALONG AND FERTILIZE HER EGGS. THEN SHE PRODUCES THOUSANDS OF NEW PARASITE LARVAE THAT SIT IN SACS WHERE THE CRAB'S OWN EGG POUCH WOULD REST (3, 4). FOOLED, THE CRAB GROOMS THE SAC AS IF IT WERE ITS OWN BROOD POUCH, AND EVEN HELPS BIRTH THE PARASITE LARVAE BY BOBBING UP AND DOWN IN THE WATER.



her claws to help them on their way. Male crabs succumb to *Sacculina*'s powers as well. Males normally develop a narrow abdomen, but infected males grow abdomens as wide as those of females, wide enough to accommodate a brood pouch or a *Sacculina* knob. A male crab even acts as if he had a female's brood pouch, grooming it as the parasite larvae grow and bobbing in the waves to release them.

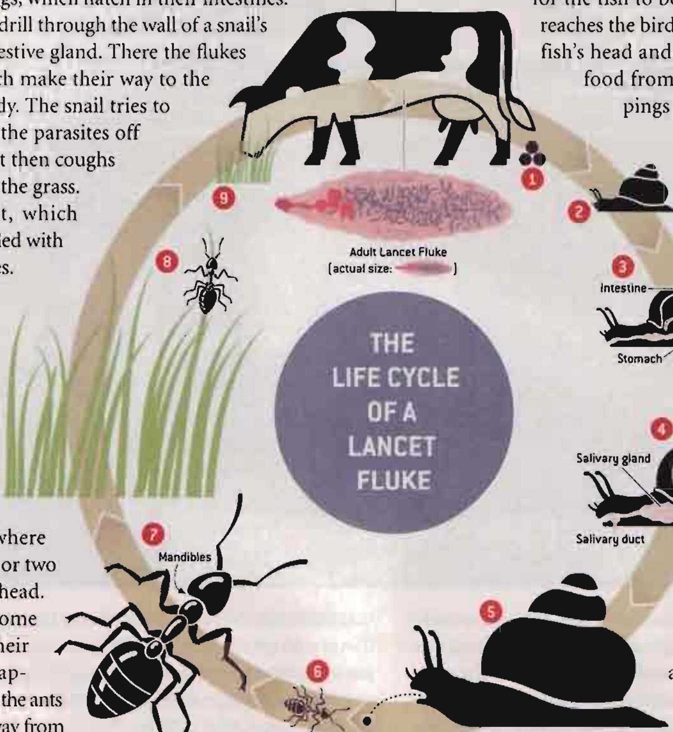
***SACCULINA*'S ADAPTATIONS REFLECT A RELATIVELY SIMPLE LIFE CYCLE** for a parasite—it makes its way from one crab to another. But for many other parasites, the game is more complicated—they must journey through a series of animal species in order to survive and procreate. Such parasites exert extraordinary control over their hosts, transforming them into seemingly different creatures. They can change a host's looks or scent to appeal to a predator. They can even alter its behavior to force it into the next host's path.

The mature lancet fluke, *Dicrocoelium dendriticum*, nestles in cows and other grazers, which spread the fluke's eggs in their manure. Hungry snails swallow the eggs, which hatch in their intestines. The immature parasites drill through the wall of a snail's gut and settle in the digestive gland. There the flukes produce offspring, which make their way to the surface of the snail's body. The snail tries to defend itself by walling the parasites off in balls of slime, which it then coughs up and leaves behind in the grass.

Along comes an ant, which swallows a slime ball loaded with hundreds of lancet flukes. The parasites slide down into the ant's gut and then wander for a while through its body, eventually moving to the cluster of nerves that control the ant's mandibles. Most of the lancet flukes head back to the abdomen, where they form cysts, but one or two stay behind in the ant's head.

There the flukes do some parasitic voodoo on their hosts. As the evening approaches and the air cools, the ants find themselves drawn away from their fellows on the ground and upward to the top of a blade of grass. Clamped to the tip of the blade, the infected ant waits to be devoured by a cow or some other grazer passing by.

If the ant sits the whole night without being eaten and the sun rises, the flukes let the ant loosen its grip on the grass. The ant scurries back down to the ground and spends the day acting like a regular insect again. If the host were to bake in the heat of the direct sun, the parasites would die with it. When evening comes again, they send the ant back up a blade of grass for another try. After the ant finally tumbles into a cow's stomach, the flukes burst out and make their way to the cow's liver, where they will live out their lives as adults.



(1) FLUKE EGGS ARE SPREAD IN COW MANURE. **(2)** A FEASTING SNAIL PICKS UP THE EGGS. **(3)** EGGS HATCH IN SNAIL'S INTESTINE. **(4)** FLUKES MATURE AND PRODUCE OFFSPRING, WHICH MIGRATE THROUGH THE HOST. **(5)** THE SNAIL WALLS OFF THE YOUNG FLUKES IN SLIME BALLS, WHICH IT COUGHS UP INTO THE GRASS. **(6)** A HUNGRY ANT SWALLOWS THE BALLS. **(7)** THE PARASITES MIGRATE INSIDE THE ANT, SOME MOVING INTO ITS ABDOMEN, OTHERS TO ITS JAWS AND BRAIN. **(8)** AT DUSK, THE PARASITES MAKE THE ANT CLIMB TO THE TIP OF A BLADE OF GRASS, WHERE IT SITS WAITING TO BE DEVOURED **(9)** BY A GRAZING COW.

AS SCIENTISTS DISCOVER MORE AND MORE PARASITES AND UNCOVER the extent and complexity of their machinations, they are fast coming to an unsettling conclusion: Far from simply being along for the ride, parasites may be one of nature's most powerful driving forces.

At the Carpinteria salt marsh, Kevin Lafferty has been exploring how parasites may shape an entire region's ecology. In a series of exacting experiments, he has found that a single species of fluke—*Euhaplorchis californiensis*—journeys through three hosts and plays a critical role in orchestrating the marsh's balance of nature.

Birds release the fluke's eggs in their droppings, which are eaten by horn snails. The eggs hatch, and the resulting flukes castrate the snail and produce offspring, which come swimming out of their host and begin exploring the marsh for their next host, the California killifish. Latching onto the fish's gills, the flukes work their way through fine blood vessels to a nerve, which they crawl along to the brain. They don't actually penetrate the killifish's brain but form a thin carpet on top of it, looking like a layer of caviar. There the parasites wait for the fish to be eaten by a shorebird. When the fish reaches the bird's stomach, the flukes break out of the fish's head and move into the bird's gut, stealing its food from within and sowing eggs in its droppings to be spread into marshes and ponds.

In his research, Lafferty set out to answer one main question: Would Carpinteria look the same if there were no flukes? He began by examining the snail stage of the cycle. The relationship between fluke and snail is not like the one between predator and prey. In a genetic sense, infected snails are dead, because they can no longer reproduce. But they live on, grazing on algae to feed the flukes inside them. That puts them in direct competition with the marsh's uninfected snails.

To see how the contest plays out, Lafferty put healthy and fluke-infested snails in separate mesh cages at sites around the marsh. "The tops were open so the sun could shine through and algae could grow on the bottom," says Lafferty. What he found was that the uninfected snails grew faster, released far more eggs, and could thrive in far more crowded conditions. The implication: In nature, the parasites were competing so intensely that the healthy snails couldn't reproduce fast enough to take full advantage of the salt marsh. In fact, if flukes were absent from the marsh, the snail population would nearly double. That explosion would ripple out through much of the salt marsh ecosystem, thinning out the carpet of algae and making it easier for the snails' predators, such as crabs, to thrive.

Lafferty then studied the killifish. Initially, he found little evidence that flukes harmed or changed the fish they colonized; the fish didn't

LEFT: THIS PARASITE CRUSTACEAN DEVOURS A FISH'S TONGUE AND REPLACES IT WITH ITSELF, WHICH THE FISH CAN USE TO GRASP PREY. ABOVE: PARASITIC WASPS LAY THEIR EGGS ON CATERPILLARS, WHICH BECOME FOOD FOR THE GROWING LARVAE. BELOW: TO GET TO ITS BIRD HOST, GREEN-STRIPED FLUKES LODGE IN THE TRANSPARENT EYE TENTACLES OF SNAILS. A BIRD SPYING THE SNAIL ON THE LEFT WILL THINK IT'S FOUND A JUICY CATERPILLAR.

even mount an immune response. But Lafferty was suspicious. He figured that flukes sitting on the brain were in a good position to be doing something. So he plucked 42 fish from the marsh, dumped them into a 75-gallon aquarium in the lab, and gave his student Kimo Morris the laborious task of watching them. Morris would pick out one fish and stare at it for half an hour, recording every move it made. When he was done, he'd scoop the fish out and dissect it to see whether its brain was caked with parasites. Then he'd focus on another killifish.

What was hidden to the naked eye came leaping out of the data. As killifish search for prey, they alternate between hovering and darting around. But every now and then, Morris would spot a fish shimmying, jerking, flashing its belly as it swam on one side, or darting close to the surface—all risky things for a fish to do if a bird is scanning the water. It turns out that fish with parasites were four times more likely to shimmy, jerk, flash, and surface than their healthy counterparts.

Lafferty and Morris followed up with a marsh experiment in which they set up two pens, each filled with 53 uninfected killifish and 95 infected fish. To distinguish between the two groups, the researchers clipped the left pectoral fin of the healthy fish and the right fin of the parasitized ones. One pen was covered with netting to protect it from birds; the other was left open so birds could easily wade or land inside. After two days, a great egret waded into the open pen. It stepped slowly into the muddy water and struck it a few times, the last time bringing up a killifish. After birds had visited the pen for three weeks, Lafferty and Morris added up how many fish were alive. (The covered pen acted as a control for the researchers to see how many fish died of natural causes.) The results were startling: The birds were 30 times more likely to feast on one of the flailing, parasitized fish than on a healthy fish.

Predators are often very careful about the prey they eat, avoiding poisonous insects and frogs, for example. So why would birds pick so many fish that are guaranteed to pass on an energy-sucking intestinal parasite? The flukes do drain a bit of energy from the birds. But that is more than offset by the benefit they provide: They make finding food very easy for the birds.

Scientists have been stunned by the implications of these findings. The birds that frequent coastal wetlands depend on fish for much of their diet. Without parasites throwing prey their way, the birds of Carpinteria might have to put far more time and effort into eating and might reproduce at a lower rate. "Could we have so many birds out there if it were 30 times harder for them to get their food?" asks marine biologist Armand Kuris, also of the University of California at Santa Barbara. "Parasites don't just modify individual behavior, they're really powerful—they may be running a large part of the waterbird ecology."

The fluke that Lafferty studied is but one parasite, living in one salt marsh. There are a dozen other species of fluke that live in the snails of Carpinteria and other parasites that dwell in other animals of the marsh. Every ecosystem on Earth is just as rife with parasites that can exert extraordinary control over their hosts, riddling them with disease, castrating them, or transforming their natural behavior. Scientists like Lafferty are only just beginning to discover exactly how powerful these hidden inhabitants can be, but their research is pointing to a remarkable possibility: Parasites may rule the world.

The notion that tiny creatures we've largely taken for granted are such a dominant force is immensely disturbing. Even after Copernicus took Earth out of the center of the universe and Darwin took humans out of the center of the living world, we still go through life pretending that we are exalted above other animals. Yet we know that we, too, are collections of cells that work together, kept harmonized by chemical signals. If an organism can control those signals—an organism like a parasite—then it can control us. And therein lies the peculiar and precise horror of parasites. ☒