In some of the first studies of learning in *C. elegans*, Rankin and other researchers are finding a surprising amount of plasticity in its nervous system. "It's not simply hard-wired," she says. And that's a tantalizing finding for researchers interested in the cellular and molecular roots of learning, because the roundworm comes with something no other organism has: a complete wiring diagram of its 302-neuron nervous system, worked out in the mid-1980s.

So far, Rankin has concentrated on pinning down the kinds of learning the worm is capable of. She has found that the "touch" and "tap" reflexes ordinarily inhibit each other: touch a worm's tail before tapping its dish and it won't back away from the tap. But after repeated, innocuous tail touches, a worm becomes habituated to them. A further tail touch no longer inhibits its response to a tap. The more experience a worm has with tail touches, the more the inhibition is diminished. "The inhibition is plastic," says Rankin. In other words, it is subject to the worm's past experience.

Habituation is considered to be one of the simplest forms of learning. But Norman Kumar, who works in the laboratory of Derek van der Kooy at the University of Toronto, showed meeting attendees that *C. elegans* is also proving adept at higher forms of learning—specifically classical conditioning, in which an animal learns to associate two different stimuli. In a Pavlov-style experiment, Kumar divided his small subjects into two groups feeding on *E. coli*—the nematode version of the chow that Pavlov fed his dogs—mixed with sodium or chloride ions. Those who got the sodium solution were then exposed to chloride without the appetizing *E. coli*, while their counterparts were exposed to sodium alone.

Kumar then tested for learning by putting the worms between gradients of the two ions, with no food present. After one round of training almost 70% of the worms moved toward the ion that had been paired with *E. coli*. When the worms had been starved for 5 hours before their training, the percentage that learned which ion went with food rose to almost 80%. And the worms remembered their lessons: A statistically significant preference for the food-associated ion lasted at least 7 hours.

The worm even seems capable of developing a conditioned aversion. When the *E. coli* was replaced with garlic extract, the worms avoided the paired ion. ("There may or may not be homology in vampires," Kumar deadpanned to the meeting.)

In the wake of these experiments, the Rankin team and Kumar *et al.* are starting to combine their results on learning with the wealth of existing knowledge about *C. elegans*' genetics and cellular development. The Toronto group is proceeding with studies of mutant strains that are deficient in certain kinds of learning, while Rankin's lab is examining what happens to learning when particular neurons in the worm's touch circuitry are knocked out by laser pulses. Rankin says that *C. elegans* promises nothing less than "the possibility of understanding the role of each cell in learning."

Roundworm as Canary?

C. elegans, darling of developmental biologists, neurobiologists, and sequencers, is making its debut in another field: ecotoxicology. Susan Anderson, an environmental toxicologist at Lawrence Berkeley Laboratory, and her collaborators are exploring the use of *C. elegans* to monitor the genetic effects of environmental contaminants.

Biomonitors are sorely needed for environmental chores such as cleaning up toxic waste sites or monitoring wildlife habitat. Some currently available methods, such as looking for chromosome aberrations in wild-caught fish, are cumbersome and unstandardized; others, based on bacterial assays, are hard to extrapolate to higher animals.

Anderson thinks *C. elegans*, an easy-to culture, multicellular animal, offers the potential of assays that would be standardized, convenient, and much easier to apply than bacterial screens. Worm-based bioassays would also be versatile: the worm normally lives in soil but can also survive in water, creating the possibility of one monitor for air, water, soil, and sediment samples. "The very significant thing is that you could use *C. elegans* in so many media," says Anderson. "There really isn't anything else like that."

Her group has developed an assay based on a mutant *C. elegans* strain. The mutant worms are paralyzed, but genetic changes triggered by exposure to a mutagenic chemical result in motile progeny. The workers are now testing the motile-worm assay on sediment samples from San Francisco Bay.

Many chemical contaminants become mutagenic in mammals only when the animal's own metabolism chemically activates them. To extend the roundworm assay to such substances, Anderson's group is studying the effectiveness of mixing rat enzymes into a sample before exposing the worms to it. "If we get a good range of metabolic activation," says Anderson, "I'm convinced that the test can be very widely applied." ■ CHRISTINE MLOT

Christine Mlot is a free-lance writer based in Milwaukee, Wisconsin.

Can Earth's Internal

When the first deep-sea hot springs were discovered off the Galápagos Islands in 1977, their biological importance was immediately apparent. They were oases of lush life, of worms and crabs and giant clams, in the otherwise sparsely inhabited abyss. More important, they turned out to be an entirely new kind of ecosystem, one sustained not by the sun's energy but by chemicals spewed out by the vents.

In the decade and a half since that dramatic discovery, countless other vents have been spotted along the globe-girdling system of mid-ocean ridges, and biologists and geophysicists have been probing the secrets of the volcanic springs and the ecosystem they sustain. Physical oceanographers, who study the circulation of the ocean itself, have been slower to get into the act. After all, ocean currents, like most ocean life, are generally thought to be driven by energy from the sun rather than from Earth's interior. But new evidence suggests that in parts of the ocean depths, heat coming out of the vents may be more important. Escaping in buoyant plumes, it may churn the abyssal waters in vast, sluggish gyres.

"People have never thought much about the physical effects of vents," says Stephen C. Riser of the University of Washington, one of the oceanographers who have collected the new evidence, which he and his colleagues announced at a recent meeting of the Oceanography Society in St. Petersburg. "But if vents generate their own flow field, it would be a ready [means of] mixing all sorts of chemicals and biology into the deep sea."

Like many of the most interesting ideas in modern physical oceanography, this one can be traced to Henry Stommel of the Woods Hole Oceanographic Institution. In 1981 Stommel, who had laid much of the groundwork for the modern understanding of ocean currents in the 1950s and 1960s, learned of a remarkable discovery made by Scripps Institution oceanographers. On a transect across the East Pacific Rise, a mid-ocean ridge dotted with hydrothermal vents, John Lupton and Harmon Craig had detected an immense plume of water laden with excess helium emanating from the ridge around 15 degrees south of the Equator, at a depth of around 2500 meters. The plume vanished immediately to the east of the ridge, but to the west Lupton and Craig tracked it more than 2000 kilometers. Clearly, the researchers concluded in a paper published in *Science*, the helium plume was acting as a tracer of the ambient

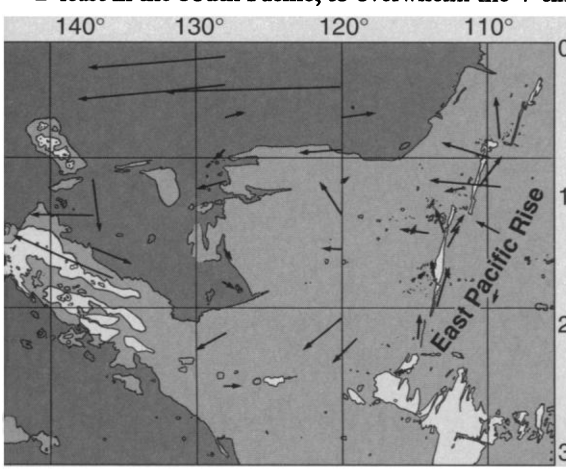
Heat Drive Ocean Circulation?

current, like "a volcanic cloud injected into a steady east wind."

Stommel was intrigued, not least because the finding seemed to conflict with a theory that he and Arnold Arons, now at the University of Washington, had devised in the late 1950s to describe the circulation of the deepest waters. In that model, which still reigns today, cold, salty, dense water sinks from the surface into the abyss at two places: the Greenland Sea in the north and the Weddell Sea in the Antarctic. From those two sources the water flows toward the equator in strong currents that hug the western boundaries of the ocean basins. At every latitude some of the water turns eastward. Thus the model predicts a deep flow that is generally west-to-east in the interior of the South Pacific. But this was precisely counter to the trajectory of the helium plume. "Evidently," Stommel wrote in a 1982 paper in ***Earth and Planetary Science Letters*** responding to Lupton's and Craig's discovery, "some discussion is called for."

To generate such a discussion, Stommel proposed a solution in the very same paper: Maybe the plume isn't just being carried along on the general circulation, like a cloud on a watery wind. Maybe it is driving its own circulation, one that is strong enough, at least in the South Pacific, to overwhelm the general flow he and Arons had sketched out more than 2 decades before.

Rossby



Caught in a gyre? ***Deep-diving floats are swept westward from the East Pacific Rise 15 degrees south of the Equator.***

The source of the anomalous westward flow, Stommel argued, is the water that bubbles out of the vents at 300 degrees Celsius. The hot water rises buoyantly, mixing with and dragging along great masses of the very cold surrounding water. By the time the plume rises several hundred meters above the ridge crest, it has cooled enough to reach a new equilibrium, at which point it starts to spread out horizontally. The outward flow is deflected by the Coriolis effect—a result of Earth's rotation—until it is circling around the source in a great gyre, like the winds circling an atmospheric high. The gyre rotates counterclockwise, because in the Southern Hemisphere the Coriolis effect twists any flow to the left.

But because the Coriolis effect varies with latitude—it is zero at the Equator and gets progressively stronger toward the poles—the flow around the 15-degree south plume is not symmetric. In Stommel's model, water flowing south out of the plume feels a Coriolis force strong enough to triumph over the outward pressure. That water gets bent around in a tight loop, back toward the center. Water flowing north out of the plume, on the other hand, gets deflected to the west—but by then it is so near the Equator, and the Coriolis force is so weak, that it just keeps on going. Thus the vent itself creates the current that sweeps the helium cloud to the west.

Stommel's model didn't win a lot of converts at first. "Stommel's theory was controversial," says Riser. "It was considered overly simple. There were a number of prominent people who just dismissed it out of hand—who said it has nothing to do with reality. But to some of us it seemed like all of Stommel's models: simple but with a seed of truth."

Riser, Thomas Rossby of the University of Rhode Island, and Lupton, now at the University of California at Santa Barbara, decided to test the idea. In 1987, on a 74-day cruise from Tahiti to Easter Island, they surveyed water throughout the entire helium plume, measuring temperature and salinity as well as helium. They also deployed 48 of Rossby's current-tracking "RAFOS" drifters—five-foot-long glass tubes precisely ballasted to match the density of sea water (and thus float) at a depth of 2600 meters—smack in the plume. After 18 months 45 of the 48 floats surfaced, carrying records of their trials, and this year Rossby finished plotting the tracks.

You'd have to squint pretty hard at the map Rossby presented in St. Petersburg to see the full counterclockwise gyre Stommel predicted, but it's easy enough to spot the part along the East Pacific Rise. South of 15 degrees, the floats follow the ridge, heading north. But just north of 15 degrees—right around the source of the plume—the trajectories break away from the ridge and head west. The westward flight is all the more remarkable because currents flow more easily where the depth is constant—along the ridge—than where depth is changing.

It is the data on water characteristics, however, combined with a model developed by Riser's graduate student Susan L. Hautala, that really strengthens the case for the plume-driven gyre, the researchers believe. The model enabled Hautala to work backwards from the temperature and salinity measurements to calculate the pattern of currents that could best explain the data. "The inverse calculation shows unmistakably that there is a connection back to the ridge," says Riser, "and it thereby closes the circulation."

The gyre is not fast—Rossby's floats drifted along at about half a centimeter per second, roughly a hundredth of a mile per hour. But it is vast—it extends from the East Pacific Rise nearly to Tahiti, and from 10 degrees to 20 degrees south. And if Riser and his colleagues are right, it may not be the only vent-driven gyre; the East Pacific Rise, though a copious source of heat, is far from being the only such source in the ocean.

Some other oceanographers, though, are skeptical of their claim. Manuel Fiadeiro, an oceanographer at the Office of Naval Research, doesn't doubt that the researchers have traced a gyre, but he thinks it's more likely to be part of the oceanwide circulation of the South Pacific than a local anomaly, driven specifically by the vents. "I don't think there's any breakthrough," he says.

But if vent-driven gyres do exist, they may turn out to be important to more than just physical oceanographers. One of the greatest puzzles about vent communities is how the creatures have managed to spread from one vent to the next across miles of barren ocean floor. And one of the most promising hypotheses, now being tested by Lauren Mullineaux and Peter Wiebe of Woods Hole, is that hydrothermal plumes sweep up the larvae of vent organisms and carry them, as the wind carries seeds, to fertile ground. As far as that hypothesis goes, it doesn't really matter whether the "wind" that disperses the organisms is powered by the same geologic phenomenon that supplies them with a habitat. But it would make a nice picture, and it may even be true. ■ ROBERT KUNZIG

Robert Kunzig is on leave from Discover *to work on a book about oceanography.*