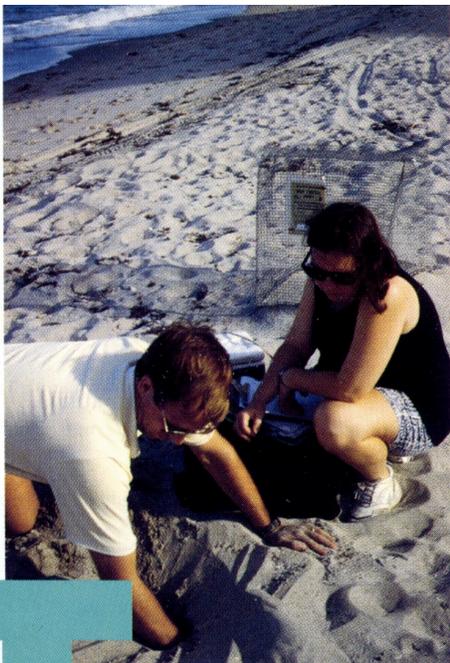


EARTHLY EATTRACTIONS

Sea turtles are uncanny navigators. New findings suggest they read Earth's magnetic field like a map.

by Dan Grossman and Seth Shulman



Dan Grossman

oting plastic coolers and wearing sunglasses to shield their eyes from the bright afternoon sun, Kenneth and Catherine Lohmann blend in well with the vacationers lounging on the beaches of Boca Raton, Florida. But the Lohmanns have not come here to enjoy the warm sand and gentle surf.

They have come to collect subjects for a research project, one that aims to find out how certain animals can navigate as confidently as if they possess maps and compasses. Such creatures are able to voyage through the open ocean for hundreds, even thousands of miles with a precision rivaling that of modern submarines. Migrating birds that return to the same breeding ground every year, bees that search far and wide for pollen and then return to their hives, salamanders that range far and wide through the woods for years and then return to their native ponds to reproduce — all have remarkable and mysterious navigating abilities. But perhaps the most amazing navigators of all are the loggerhead sea turtles that the Lohmanns have come to study.

Zigzagging through an obstacle course of picnic blankets and beach chairs, the Lohmanns finally arrive at their destination: a wire cage staked down to the sand. Ken Lohmann lifts the battered enclosure and digs into the sand with his hands.

“Here they are,” he says after a few minutes of careful excavation. He lifts from the nest a handful of three-inch-long hatchling sea turtles. Only hours old, they are miniature versions of their lumbering parents, already equipped with sturdy carapaces, scaly legs and beaklike mouths. Working swiftly now, Lohmann loads a dozen of the wriggling reptiles into a cooler and closes the lid tight.

The young turtles are gawky and barely the size of a child’s fist. Yet later this evening they will embark on a journey through thousands of miles of trackless sea. Heading east, the hatchlings will ride the Gulf Stream into a system of currents that encircles the North Atlantic Ocean, called a gyre. Within the gyre lies the Sargasso Sea, a rich feeding ground for the turtles. They will wander the periphery of the Sargasso for as long as ten years, feeding on invertebrates, crustaceans and other animals that live on and near the ubiquitous sargassum, a floating brown seaweed.

Once the turtles have fattened up to an adult weight of some 300 pounds, they will head west and return to this same beach to dig nests and lay eggs. Before the newly hatched turtles are allowed to embark on this epic voyage, however, they must first spend an evening in the Lohmanns’ summer laboratory at nearby Florida Atlantic University in Boca Raton.

How do turtles navigate the oceans? Scientists have identified and studied a number of cues that may aid animal migrations, including smell, sun position, star patterns, wave direction and physical landmarks such as mountain ranges. In their most recent research, the Lohmanns have discovered compelling evidence for the long-suspected navigational system that may enable sea turtles to complete remarkable transoceanic

migrations: the ability to sense Earth’s magnetic field. Scientists have suspected such a link for more than a century. But concrete evidence for animal magneto-reception, as it’s called, remained elusive until 30 years ago. In the mid-1960s, a burst of research showed that migratory birds do indeed use Earth’s magnetism to navigate. Since then, researchers have found additional evidence suggesting that other kinds of animals, from bacteria to whales, may also sense magnetic fields.

Scientists have linked magnetic reception to a variety of animal behaviors, including beehive construction and the unerringly precise tunneling of African mole rats. One hotly disputed series of experiments has even suggested that humans can sense Earth’s magnetic field and may use it for orientation. In their search for the underlying biological machinery of magnetic reception, scientists have found crystals of magnetite in the brain tissues of several different kinds of animals. Magnetite, a naturally magnetic mineral that is sensitive to Earth’s magnetic field, may provide these creatures with a sort of internal compass needle. This remains controversial, however, because nobody has yet shown how particles of magnetite in the brain actually give rise to a compass sense.

The role of magnetite in animal navigation is not the only outstanding mystery about magneto-reception. Ken Lohmann says two key issues await complete solutions. One is how animals detect magnetic fields. The other is how

Top: Catherine and Kenneth Lohmann collect loggerhead turtle hatchlings on the beach at Boca Raton, Florida.

Right: Loggerhead sea turtles are among the world’s greatest navigators. They spend much of their lives in the Sargasso Sea, a fertile region in the middle of the Atlantic. But mature loggerheads travel thousands of miles to return to their natal beaches to reproduce.



Yves Lanceau/Jacana/Photo Researchers, Inc.

they use this magnetic information to find their way. The Lohmanns' work with loggerheads is providing intriguing new clues about about magnetoreception in turtles. Last fall, they published a study in the *Journal of Experimental Biology* offering evidence that loggerheads use a specific feature of Earth's magnetic field to make a key course change during their migration to the Sargasso Sea. The Lohmanns are excited and encouraged by their findings. "We may be on the verge of some tremendous advances," Ken Lohmann says.

Loggerheads and the six or seven other species of sea turtles that inhabit the world's oceans are especially good candidates for research on magnetoreception because they are believed to navigate a significant fraction of the time in the oceans' dark depths. With few other cues available, sea turtles may, at least part of the time, rely primarily on Earth's magnetic field to navigate. Sea turtles also make some of the longest voyages of any animal, and they are extraordinarily successful at locating their natal beaches, or birthplaces.

One population of green sea turtles, for instance, cruises through 2,000 miles (3,200 km) of open ocean to feed near the coast

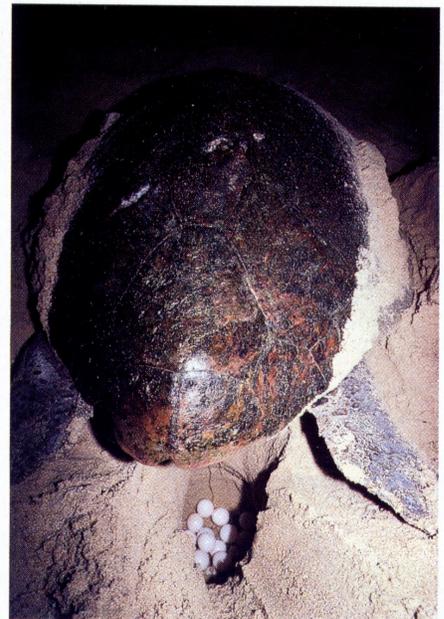
of Brazil and then return to its nesting area on tiny Ascension Island. Even more impressive, it is widely believed that Kemp's Ridley turtles always return to lay their eggs on a single beach in Rancho Nuevo, a town on the gulf coast of Mexico.

From birth, says Ken Lohmann, loggerheads show a powerful urge to hit the beaches and begin their migrations. That's a help to researchers who want to study the role of magnetoreception in migration thoroughly and repeatedly. Besides, Lohmann adds, he has been fascinated by reptiles and amphibians since childhood. "Growing up in Indiana," he says, "I had frogs, turtles, toads, snakes. My room was a menagerie."

Despite the current usefulness of turtles for studies of magnetoreception, it was research on birds that provided the earliest clues to its biological basis. In 1965, German biologists Wolfgang Wiltschko and Friedrich Merkel reported the first evidence that birds use Earth's magnetic field as a reference point in their airborne navigations. The scientists discovered that European robins, when their view of the sky was blocked, con-

Left: After mating, the female loggerhead returns to her natal beach to nest. Here, a loggerhead crawls ashore at Tenerife in the Canary Islands off Spain.

Below: Once ashore, she digs a hole in the sand and deposits her eggs. This particular turtle is on the coast of Kwazulu-Natal, South Africa.



M. Reardon/Photo Researchers, Inc.

sistently attempted to escape their cages in a southwesterly direction — the same direction the birds fly during normal migrations. Moreover, the scientists could change the robins' preferred escape route by exposing them to a magnetic field oriented differently than Earth's.

In an influential series of experiments in the early 1970s, William Keeton, then an ornithologist at Cornell University in Ithaca, New York, published work that seemed to clinch the case for magnetoreception. Keeton glued small, lightweight magnets to the heads of homing pigeons. On overcast days, the magnets caused the pigeons to lose their way — presumably by distorting the natural magnetic field surrounding the birds. Pigeons outfitted with unmagnetized pieces of brass, however, found their way home without difficulty. On sunny days, both groups of birds could navigate



Larry Cameron/Photo Researchers, Inc.

Left: When the egg clutch is complete, the female covers the hole and returns to the sea — here, in South Carolina. The turtles hatch under the sand, dig their way out and crawl into the sea. Below: As part of a research project on the Florida coast, the Lohmanns dig up hatchling turtles and study their navigating abilities before releasing the newborns into the surf.

just fine whether they were wearing magnets or brass weights. These elegant and convincing experiments lent strong support to the idea that birds use magnetic sensing to navigate. But since the birds needed their magnetic sense only on overcast days, magnetoreception presumably serves primarily as a backup when visual clues such as the sun and stars are unavailable. Although recent experiments by other researchers have not produced exactly the same results as Keeton's, a clutch of other studies has confirmed his basic discovery: that a variety of migrating birds detect the geomagnetic field and use it to navigate.

If birds and other animals can sense magnetic fields, where are the sensors and how do they work? In 1979, a team at Princeton University suggested a possible answer. They found crystals of magnetite in brain tissues of pigeons. (It has also been found in the skulls of sea turtles.) Joseph Kirschvink, one of the Princeton researchers, later discovered magnetite in human brain tissue as well.

The Princeton team speculated that the magnetite crystals would attempt to align with Earth's magnetic poles just like a compass needle. The movement of the crystals would create a force inside the animal's brain that would provide information about its orientation with reference to Earth's magnetic field. According to this theory, the animal's brain would use this information like a guided missile uses gravitational information from a gyroscope to keep track of changes in its position relative to Earth's surface.



Seth Shulman

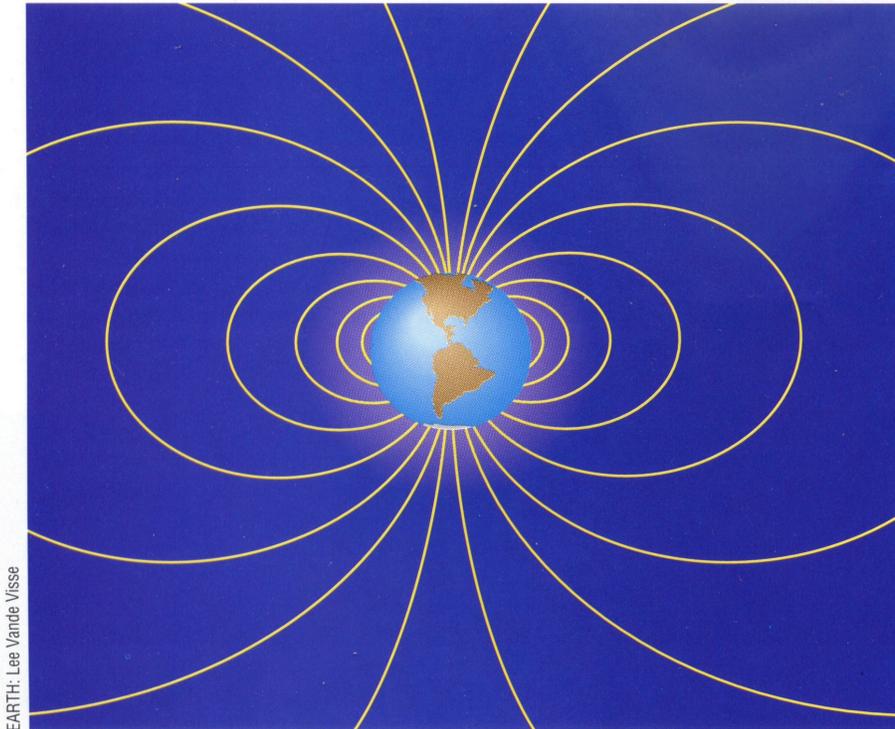
Kirschvink says the discovery of magnetite in the brains of birds and other animals "opened up a whole new ball game." It immediately provided a plausible explanation for how birds chart their positions during migrations. And it could explain the observation that honeybees always set out on searches for food heading due south, even when visual clues such as the position of the sun are absent.

But for largely theoretical reasons, a number of researchers have proposed an alternative to an internal compass based on particles of magnetite crystals in the brain. Instead, they have moved the compass sense to the eyes. If they are right, then some migrating animals may perceive magnetic fields similar to the way we perceive the contour lines of a topographic map.

John Phillips, an expert in magnetic reception at Indiana University in Bloomington, is one

of a growing number of researchers who favor a magnetic sensing mechanism that is based in the eye rather than the brain. The theory was born in 1977, when Michael Leask, a physicist at Oxford University in England, proposed that pigment molecules in a bird's retina, when exposed to light at the right frequency, could become magnetically polarized. This means the pigment molecules essentially begin to behave like tiny bar magnets and can therefore respond to the contours of Earth's magnetic field. Leask dubbed the theory "optical pumping," because it is based on the idea that the pigment molecules are somehow pumped into an excited, magnetically sensitive state by light entering the eye.

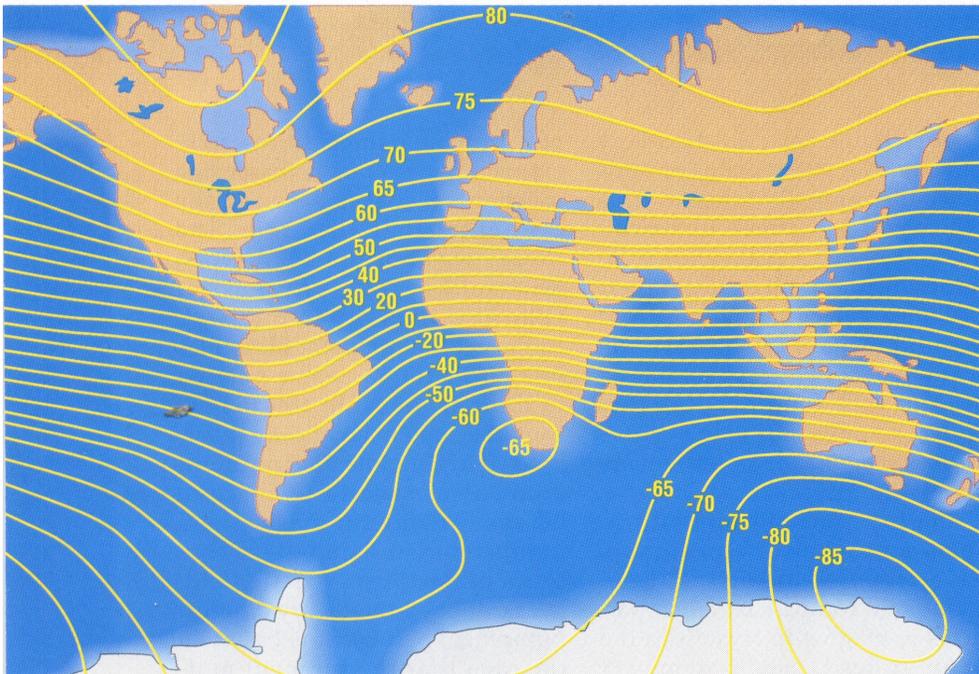
In 1992, Phillips obtained the first real experimental evidence for the theory. His research focused on a migratory, amphibious salamander called the red-spotted newt. In contrast to sea turtles,



EARTH: Lee Vande Visse

Earth is enveloped by a magnetic field generated by the motion of its iron core. The magnetized needle of a compass will align itself parallel to the field lines that sweep from pole to pole. Animals seem to have a similar, internal compass that helps them find their way during migrations.

EARTH: Lee Vande Visse



Recent studies suggest that sea turtles use the changing angle of Earth's magnetic field with respect to the ground, called the angle of inclination, to navigate the oceans. In the above diagram, each line represents points on the globe that share the same angle of inclination. Thus, at all points along the line marked by the number 40, Earth's magnetic field forms an inclination angle of 40 degrees. The waviness of the lines reflects the fact that the inclination of the field only roughly mirrors changing latitude. Some animals may use changing inclination to navigate.

newts lay eggs in water after some five years of terrestrial living. To do so, they journey a considerable distance to the pond where they were born. In laboratory experiments, Phillips discovered that the newts' sense of orientation could be manipulated by exposing them to different colors of light. This meant that a newt's magnetic sense is intimately connected to its visual perception. It also fit with Leask's theory that light of the right frequency could turn pigment molecules in the retina into tiny compass needles. In a recent experiment, a team of researchers in Australia found evidence of a similar magnetoreception system in a migratory bird called the Australian silvereye.

The problem with this theory for some researchers is that the system is driven by light. However, these critics point out, turtles and other animals seem to have the ability to navigate in the dark. To answer this criticism, Phillips has proposed that magnetic reception in the eye could be powered by internal chemical reactions instead of ambient light. In fact, he says he has preliminary evidence of such a chemical engine in the eyes of fruit flies. Yet even Phillips admits this is speculative and not the best answer to criticisms of the theory.

But whether the internal compass some animals possess is based in the brain or the eye, other equally important questions remain unanswered. The main problem is that a simple compass provides only orientation — which direction the animal is going — but not a sense of which direction it *should* be going to reach its destination. With only a simple compass, how would a bird know when to change direction? In its winter flight from Europe, for example, the garden warbler heads southwest from Germany until it passes over Spain. Then it starts flying southeast across Africa. Somehow this warbler knows

when it must change direction over Spain.

And then there's the famous Monarch butterfly. Every year, as winter approaches, 100 million Monarchs fly from all over North America and converge on one small, isolated mountain forest in central Mexico. Because the butterflies are widely dispersed in the summer months, an internal compass alone would not be sufficient equipment for them to find their winter home. It's as if each animal carries a tiny map of the world in its head and uses its internal compass to find its way around within that map.

Similarly, loggerheads seem to possess some kind of map sense. Otherwise, how could they circle the Sargasso Sea for years and then turn around and return to a specific and relatively small part of the Florida coast? "A migrating animal requires two main pieces of information: compass information to maintain direction and map information to work out where it is and where it wants to go," says Wiltschko, currently at the Johann Wolfgang Götte University in Frankfurt, Germany.

Some researchers believe that information from Earth's magnetic field could provide that "map sense." This is because Earth's field contains a wealth of clues that an animal with a sensitive enough magnetic reception system could use to locate any dot of land on the planet.

Although the effects of Earth's magnetic field can be observed by anyone who dangles a magnetized needle from a thread (it will turn until aligned parallel with the field), its physical origin is not completely understood. Indeed, Albert Einstein once called Earth's magnetic field one of the five great unsolved questions of physics.

According to Raymond Jeanloz, a professor of geology and geophysics at the University of California, Berkeley, Earth's magnetic field originates deep within the planet. Although the field at Earth's surface resembles the field produced by a simple bar magnet, scientists have known for decades



Dan Grossman

Once the Lohmanns have the turtles in the lab, they put them in Lycra "bathing suits." These enable the researchers to connect the hatchlings to a turtle tracking system that measures the influence of magnetism on the direction turtles choose to swim.

that the pressure and heat inside the planet are too intense for any solid material to remain permanently magnetized. Instead, Earth's field is thought to be powered by a dynamic process. According to current theory, our planet actually contains a giant electromagnet that works on the same principles as the magnets used in junkyards to pick up scrap metal.

Geomagnetism originates in Earth's core, which begins about 1,800 miles (2,900 km) beneath the surface. The outermost layer of the core, composed of an iron-rich alloy, is a superhot fluid. The complex motion of this fluid, driven by Earth's rotation, both creates and continually regenerates the planet's ancient magnetic field. It's a dynamic, self-reinforcing process. If this were not the case — if the planet were simply the equivalent of a static bar magnet — the field would have winked out after about 10,000 years. Earth's magnetic field, however, has probably existed for 2.5 billion to 3.5 billion years.

Although this explanation for geomagnetism is widely accepted, experimental evidence remains scarce. From the surface, the globe's magnetic field appears as if it were produced by an enormous bar magnet plunged

through the planet along its axis of rotation. The north magnetic pole is located close to the north geographic pole; the south magnetic pole is similarly close to its geographic counterpart. The field is ubiquitous across the planet, but it is exceedingly weak compared with fields easily produced in laboratories or even at home. The field strength, measured in units called gauss, varies with latitude. Depending on where one stands, the intensity of Earth's magnetic field ranges from 0.3 to 0.5 gauss. In contrast, the field strength near a child's toy magnet can easily reach 100 gauss.

The intensity of Earth's field does not change in even steps with changing latitude, however, and animals may exploit this to keep track of where they are. Within Earth's seemingly smooth magnetic field lie small blips of field intensity, called magnetic anomalies. At these points, the field's intensity dips or rises. These blips are slight — generally between $1/100$ and $1/1,000$ of a gauss. And the pattern formed by the blips is every bit as intricate as a topographic map, which shows changes in elevation on Earth's surface. Some anomalies in Earth's field, like mountains towering over flat plains, cause local variations of more than one gauss in the space of just a few miles.

Such a disturbance near the Finnish Island of Jassarö has reputedly caused numerous shipwrecks by shifting seafarers' compass readings. Some animal navigation researchers believe that the pattern of Earth's magnetic anomalies across the globe might provide map information needed by migrating animals to find their way.

Although the intensity of Earth's field differs depending on where you stand, it is generally greatest near the magnetic poles and weakest at the equator. As the field lines emerge from the poles and sweep over Earth's surface, the angle they form relative to the ground changes incrementally. And the changing inclination of the field mirrors its changing intensity: With decreasing latitude, the magnetic force grows ever weaker. At the magnetic poles, for example, the inclination of the field is about 90 degrees. This means that at the poles the invisible field lines are nearly perpendicular to the surface of the planet. In contrast, at the equator, the inclination of Earth's magnetic field is zero degrees.

That means the field lines flow parallel to the surface. Thus, magnetic inclination is a pretty good stand-in for latitude: The changing angle of inclination of Earth's magnetic field may tell a magnetoreceptive animal how far it is from the poles. And the complex pattern of anomalies in the field, like the mountains and valleys marked on a topographic map, could conceivably be used to determine longitude, some researchers believe.

Recent research by the Lohmanns suggests that loggerheads can detect changes in the inclination of Earth's field and use this information to navigate the ocean. In their experiments, the Lohmanns tethered hatchling loggerheads to what they call their "turtle tracking system." Each turtle was placed in a tiny, Lycra swimsuit

that allowed the Lohmanns to attach a short length of fishing line to the back of each animal. Each harnessed turtle was placed in a tub of water the size and shape of a child's pool and tethered by its line to a swinging arm. The freely rotating arm allowed the turtle to swim in place in any compass direction it chose. A computer tracked and plotted the movements of the arm. The overall trajectory of these movements, analyzed statistically, reflects the swimming orientation chosen by the majority of the hatchlings.

Most important, the angle of inclination of the magnetic field surrounding the tub could be varied in 15-degree increments. To do this, the Lohmanns surrounded the swimming pool with a cage-like structure of wire-wrapped plastic pipes. Using a computer to alter the way in which current was delivered to the wire coils, the Lohmanns could mimic the inclination of the local magnetic field at a variety of locations on the planet.

In a series of experiments in 1993, the Lohmanns expected the turtles to swim east when the magnetic inclination was set at 60 degrees — close to the 57 degrees found on the Boca Raton beach. After all the Gulf Stream, which the turtles follow to get to the Sargasso Sea, lay due east of the beach, and that is presumably where every hatchling ultimately wanted to go. But the turtles did not always swim east. In fact, at 60 degrees the turtles exhibited a clear and confounding tendency to swim south. At first, this seemed inexplicable to the Lohmanns. The scientists had to figure out why a three-degree difference in inclination had made such an important difference to the turtles.

As it turned out, in the wild that slight variation could mean the difference between life and death. Consulting a map that charts the inclination of Earth's magnetic field, the Lohmanns discovered that an inclination of 60 degrees occurs in the Atlantic Ocean near a point where the

Gulf Stream undergoes an important change. At that point, the turtles must make a fateful choice — to head south instead of north. There, off the coast of Portugal, the current splits. One branch flows north toward Great Britain and the other swings south toward Africa. Should a turtle wander into the northern branch, it would be carried into colder northern waters and die.

The Lohmanns' subsequent experiments confirmed that the turtles can sense a change as small as three degrees in inclination, and they may well be considerably more sensitive than that. In the lab, hatchlings exposed to the inclination angle of their birthplace (57 degrees) by and large swam eastward, just as expected.

These experiments provided the first evidence that sea turtles can detect changes in the inclination of Earth's magnetic field. The Lohmanns suspect that when the hatchlings grow to adulthood, they are still somehow drawn to the unique inclination of their natal beach. Once they have roamed the seas, all they need do to return to their birthplace is reverse their direction of swimming and follow the force lines home, like truck drivers following the center line of a dark highway on a foggy night.

Loggerheads may also have a sensitive enough magnetic compass to detect more subtle features of Earth's field. Last summer, the Lohmanns discovered that their hatchlings can pick up changes in magnetic intensity as well as inclination. "That's exciting because it suggests that turtles may be able to use both features — inclination and intensity — to determine their precise location in the ocean," Ken Lohmann says. If so, then the Boca Raton loggerheads may, like Monarch butterflies, carry mental maps of the world in their heads that they use to home in on their natal beaches after years of migratory wandering.



M. Reardon/Photo Researchers, Inc.

As the loggerhead hatchlings head out to sea, they are already using their powers of navigation to find their way in the world. Most will perish, however, in the jaws of predatory fish before reaching adulthood.

The ultimate answer to how animals use Earth's magnetism to navigate may be found in neuroscience. During the winter months, when hatchling loggerheads are unavailable, the Lohmanns have been probing the brains of a certain kind of giant sea slug (they reach lengths of 12 inches) that inhabits the waters near Seattle, Washington. These creatures are not as remarkable for their length, however, as for the size of their brain cells. Their neurons grow as fat as one millimeter in diameter and can actually be seen with the naked eye. Neuroscientists often use sea slugs in their research because it's relatively easy to monitor the electrical activity of their giant neurons. This helps scientists link certain basic mental functions such as learning and memory to particular neurons in the brain.

Sea slugs, says Ken Lohmann, show a strong but not well understood tendency to orient them-

selves to magnetic fields. At the University of North Carolina in Chapel Hill, where the Lohmanns teach and conduct research during the academic year, they are studying the electrical response of sea slug brains to magnetic fields.

The brain of a sea slug, explains Lohmann, resembles a bunch of grapes. And the location of the individual grapes doesn't change much from one individual slug brain to the next. Because of this, Ken Lohmann says, he and Cathy have been able to chart the response to magnetic fields of the same neurons in many individual slugs. They have discovered that four particular neurons fire off electrical signals more rapidly than normal in response to a change in the orientation of the magnetic field to which they are exposed.

Are these neurons part of the magnetoreception system of the sea slug? "If we can answer that question in a simple organism like the sea slug," says Ken Lohmann, "then we might gain insight into

how more complicated animals, such as turtles, sense magnetic fields."

But tonight in Boca Raton, it is the loggerhead turtle hatchlings that command the Lohmanns' full attention. Sometime after midnight, after they have put the newborn turtles through their paces in the turtle tracking system, the scientists carry their hatchling-filled coolers back to the beach. There, turtles are just now beginning to emerge from their buried nests. Gently, the Lohmanns release the hatchlings to the world with the care of devoted naturalists. The couple watches in wistful silence as the small turtles march into the dark ocean. ⊕

Dan Grossman and Seth Shulman are science journalists based in Boston. In the March 1994 issue of Earth, they reported on the proposed nuclear waste storage site at Yucca Mountain in Nevada.