CHAPTER 9

# Polymers Are Forever

THE PORT OF Plymouth in southwestern England is no longer listed among the scenic towns of the British Isles, although prior to World War II it would have qualified. During six nights of March and April 1941, Nazi bombs destroyed 75,000 buildings in what is remembered as the Plymouth Blitz. When the annihilated city center was rebuilt, a modern concrete grid was superimposed on Plymouth's crooked cobbled lanes, burying its medieval past in memory.

But the main history of Plymouth lies at its edge, in the natural harbor formed at the confluence of two rivers, the Plym and the Tamar, where they join the English Channel and the Atlantic Ocean. This is the Plymouth from which the Pilgrims departed; they named their American landfall across the sea in its honor. All three of Captain Cook's Pacific expeditions began here, as did Sir Francis Drake's circumnavigation of the globe. And, on December 27, 1831, H.M.S. *Beagle* set sail from Plymouth Harbor, with 22-year-old Charles Darwin aboard.

University of Plymouth marine biologist Richard Thompson spends a lot of time pacing Plymouth's historic edge. He especially goes in winter, when the beaches along the harbor's estuaries are empty—a tall man in jeans, boots, blue windbreaker, and zippered fleece sweater, his bald pate hatless, his long fingers gloveless as he bends to probe the sand. Thompson's doctoral study was on slimy stuff that mollusks such as limpets and winkles like to eat: diatoms, cyanobacteria, algae, and tiny plants that cling to seaweed. What he's now known for, however, has less to do with marine life than with the growing presence of things in the ocean that have never been alive at all.

Although he didn't realize it at the time, what has dominated his life's work began when he was still an undergraduate in the 1980s, spending autumn weekends organizing the Liverpool contingent of Great Britain's national beach cleanup. In his final year, he had 170 teammates amassing metric tons of rubbish along 85 miles of shoreline. Apart from items that apparently had dropped from boats, such as Greek salt boxes and Italian oil cruets, from the labels he could see that most of the debris was blowing east from Ireland. In turn, Sweden's shores were the receptacles for trash from England. Any packaging that trapped enough air to protrude from the water seemed to obey the wind currents, which in these latitudes are easterly.

Smaller, lower-profile fragments, however, were apparently controlled by currents in the water. Each year, as he compiled the team's annual reports, Thompson noticed more and more garbage that was smaller and smaller amid the usual bottles and automobile tires. He and another student began collecting sand samples along beach strand lines. They sieved the tiniest particles of whatever appeared unnatural, and tried to identify them under a microscope. This proved tricky: their subjects were usually too small to allow them to pinpoint the bottles, toys, or appliances from which they sprang.

He continued working the annual cleanup during graduate studies at Newcastle. Once he completed his Ph.D. and began teaching at Plymouth, his department acquired a Fourier Transform Infrared Spectrometer, a device that passes a microbeam through a substance, then compares its infrared spectrum to a database of known material. Now he could know what he was looking at, which only deepened his concern.

"Any idea what these are?" Thompson is guiding a visitor along the shore of the Plym River estuary, near where it joins the sea. With a full moonrise just a few hours off, the tide is out nearly 200 meters, exposing a sandy flat scattered with bladderwrack and cockle shells. A breeze skims the tidal pools, shivering rows of reflected hillside housing projects. Thompson bends over the strand line of detritus left by the forward edge of waves lapping the shore, looking for anything recognizable: hunks of nylon rope, syringes, topless plastic food containers, half a ship's float, pebbled remains of polystyrene packaging, and a rainbow of assorted bottle caps. Most plentiful of all are multicolored plastic shafts of cotton ear swabs. But there are also the odd little uniform shapes he challenges people to identify. Amid twigs and seaweed fibers in his fistful of sand are a couple of dozen blue and green plastic cylinders about two millimeters high.

"They're called nurdles. They're the raw materials of plastic production. They melt these down to make all kinds of things." He walks a little farther, then scoops up another handful. It contains more of the same plastic bits: pale blue ones, greens, reds, and tans. Each handful, he calculates, is about 20 percent plastic, and each holds at least 30 pellets.

"You find these things on virtually every beach these days. Obviously they are from some factory."

However, there is no plastic manufacturing anywhere nearby. The pellets have ridden some current over a great distance until they were deposited here—collected and sized by the wind and tide.

In Thompson's laboratory at the University of Plymouth, graduate student Mark Browne unpacks foil-wrapped beach samples that arrive in clear zip-lock bags sent by an international network of colleagues. He transfers these to a glass separating funnel, filled with a concentrated solution of sea salt to float off the plastic particles. He filters out some he thinks he recognizes, such as pieces of the ubiquitous colored ear-swab shafts, to check under the microscope. Anything really unusual goes to the FTIR Spectrometer.

Each takes more than an hour to identify. About one-third turn out to be natural fibers such as seaweed, another third are plastic, and another third are unknown—meaning that they haven't found a match in their polymer database, or that the particle has been in the water so long its color has degraded, or that it's too small for their machine, which analyzes fragments only to 20 microns—slightly thinner than a human hair.

"That means we're underestimating the amount of plastic that we're finding. The true answer is we just don't know how much is out there."

What they do know is that there's much more than ever before. During the early 20th century, Plymouth marine biologist Alistair Hardy developed an apparatus that could be towed behind an Antarctic expedition boat, 10 meters below the surface, to sample krill—an ant-sized, shrimp-like invertebrate on which much of the planet's food chain rests. In the

1930s, he modified it to measure even smaller plankton. It employed an impeller to turn a moving band of silk, similar to how a dispenser in a public lavatory moves cloth towels. As the silk passed over an opening, it filtered plankton from water passing through it. Each band of silk had a sampling capacity of 500 nautical miles. Hardy was able to convince English merchant vessels using commercial shipping lanes throughout the North Atlantic to drag his Continuous Plankton Recorder for several decades, amassing a database so valuable he was eventually knighted for his contributions to marine science.

He took so many samples around the British Isles that only every second one was analyzed. Decades later, Richard Thompson realized that the ones that remained stored in a climate-controlled Plymouth warehouse were a time capsule containing a record of growing contamination. He picked two routes out of northern Scotland that had been sampled regularly: one to Iceland, one to the Shetland Islands. His team pored over rolls of silk reeking of chemical preservative, looking for old plastic. There was no reason to examine years prior to World War II, because until then plastic barely existed, except for the Bakelite used in telephones and radios, appliances so durable they had yet to enter the waste chain. Disposable plastic packaging hadn't yet been invented.

By the 1960s, however, they were seeing increasing numbers of increasing kinds of plastic particles. By the 1990s, the samples were flecked with triple the amount of acrylic, polyester, and crumbs of other synthetic polymers than was present three decades earlier. Especially troubling was that Hardy's plankton recorder had trapped all this plastic 10 meters below the surface, suspended in the water. Since plastic mostly floats, that meant they were seeing just a fraction of what was actually there. Not only was the amount of plastic in the ocean increasing, but ever smaller bits of it were appearing—small enough to ride global sea currents.

Thompson's team realized that slow mechanical action—waves and tides that grind against shorelines, turning rocks into beaches—were now doing the same to plastics. The largest, most conspicuous items bobbing in the surf were slowly getting smaller. At the same time, there was no sign that any of the plastic was biodegrading, even when reduced to tiny fragments.

"We imagined it was being ground down smaller and smaller, into a kind of powder. And we realized that smaller and smaller could lead to bigger and bigger problems."

He knew the terrible tales of sea otters choking on polyethylene rings from beer six-packs; of swans and gulls strangled by nylon nets and fishing lines; of a green sea turtle in Hawaii dead with a pocket comb, a foot of nylon rope, and a toy truck wheel lodged in its gut. His personal worst was a study on fulmar carcasses washed ashore on North Sea coastlines. Ninety-five percent had plastic in their stomachs—an average of 44 pieces per bird. A proportional amount in a human being would weigh nearly five pounds.

There was no way of knowing if the plastic had killed them, although it was a safe bet that, in many, chunks of indigestible plastic had blocked their intestines. Thompson reasoned that if larger plastic pieces were breaking down into smaller particles, smaller organisms would likely be consuming them. He devised an aquarium experiment, using bottom-feeding lugworms that live on organic sediments, barnacles that filter organic matter suspended in water, and sand fleas that eat beach detritus. In the experiment, plastic particles and fibers were provided in proportionately bite-size quantities. Each creature promptly ingested them.

When the particles lodged in their intestines, the resulting constipation was terminal. If they were small enough, they passed through the invertebrates' digestive tracts and emerged, seemingly harmlessly, out the other end. Did that mean that plastics were so stable that they weren't toxic? At what point would they start to naturally break down—and when they did, would they release some fearful chemicals that would endanger organisms sometime far in the future?

Richard Thompson didn't know. Nobody did, because plastics haven't been around long enough for us to know how long they'll last or what happens to them. His team had identified nine different kinds in the sea so far, varieties of acrylic, nylon, polyester, polyethylene, polypropylene, and polyvinyl chloride. All he knew was that soon everything alive would be eating them.

"When they get as small as powder, even zooplankton will swallow them."

Two sources of tiny plastic particles hadn't before occurred to Thompson. Plastic bags clog everything from sewer drains to the gullets of sea turtles who mistake them for jellyfish. Increasingly, purportedly biodegradable versions were available. Thompson's team tried them. Most turned out to be just a mixture of cellulose and polymers. After the cellulose starch broke down, thousands of clear, nearly invisible plastic particles remained.

Some bags were advertised to degrade in compost piles as heat generated by decaying organic garbage rises past 100°F. "Maybe they do. But that doesn't happen on a beach, or in salt water." He'd learned that after they tied plastic produce bags to moorings in Plymouth Harbor. "A year later you could still carry groceries in them."

Even more exasperating was what his Ph.D. student Mark Browne discovered while shopping in a pharmacy. Browne pulls open the top drawer of a laboratory cabinet. Inside is a feminine cornucopia of beauty aids: shower massage creams, body scrubs, and hand cleaners. Several are by boutique labels: Neova Body Smoother, SkinCeuticals Body Polish, and DDF Strawberry Almond Body Polish. Others are international name brands: Pond's Fresh Start, a tube of Colgate Icy Blast toothpaste, Neutrogena, Clearasil. Some are available in the United States, others only in the United Kingdom. But all have one thing in common.

"Exfoliants: little granules that massage you as you bathe." He selects a peach-colored tube of St. Ives Apricot Scrub; its label reads, *100% natural exfoliants.* "This stuff is okay. The granules are actually chunks of ground-up jojoba seeds and walnut shells." Other natural brands use grape seeds, apricot hulls, coarse sugar, or sea salt. "The rest of them," he says, with a sweep of his hand, "have all gone to plastic."

On each, listed among the ingredients are "micro-fine polyethylene granules," or "polyethylene micro-spheres," or "polyethylene beads." Or just polyethylene.

"Can you believe it?" Richard Thompson demands of no one in particular, loud enough that faces bent over microscopes rise to look at him. "They're selling plastic meant to go right down the drain, into the sewers, into the rivers, right into the ocean. Bite-size pieces of plastic to be swallowed by little sea creatures."

Plastic bits are also increasingly used to scour paint from boats and aircraft. Thompson shudders. "One wonders where plastic beads laden with paint are disposed. It would be difficult to contain them on a windy day. But even if they're contained, there's no filter in any sewage works for material that small. It's inevitable. They end up in the environment."

He peers into Browne's microscope at a sample from Finland. A lone green fiber, probably from a plant, lies across three bright blue threads that probably aren't. He perches on the countertop, hooking his hiking boots around a lab stool. "Think of it this way. Suppose all human activity ceased tomorrow, and suddenly there's no one to produce plastic anymore. Just from what's already present, given how we see it fragmenting, organisms will be dealing with this stuff indefinitely. Thousands of years, possibly. Or more."

IN ONE SENSE, plastics have been around for millions of years. Plastics are polymers: simple molecular configurations of carbon and hydrogen atoms that link together repeatedly to form chains. Spiders have been spinning polymer fibers called silk since before the Carboniferous Age, whereupon trees appeared and started making cellulose and lignin, also natural polymers. Cotton and rubber are polymers, and we make the stuff ourselves, too, in the form of collagen that comprises, among other things, our fingernails.

Another natural, moldable polymer that closely fits our idea of plastics is the secretion from an Asian scale beetle that we know as shellac. It was the search for an artificial shellac substitute that one day led chemist Leo Baekeland to mix tarry carbolic acid—phenol—with formaldehyde in his garage in Yonkers, New York. Until then, shellac was the only coating available for electric wires and connections. The moldable result became Bakelite. Baekeland became very wealthy, and the world became a very different place.

Chemists were soon busy cracking long hydrocarbon chain molecules of crude petroleum into smaller ones, and mixing these fractionates to see what variations on Baekeland's first man-made plastic they could produce. Adding chlorine yielded a strong, hardy polymer unlike anything in nature, known today as PVC. Blowing gas into another polymer as it formed created tough, linked bubbles called polystyrene, often known by the brand name Styrofoam. And the continual quest for an artificial silk led to nylon. Sheer nylon stockings revolutionized the apparel industry, and helped to drive acceptance of plastic as a defining achievement of modern life. The intercession of World War II, which diverted most nylon and plastic to the war effort, only made people desire them more.

After 1945, a torrent of products the world had never seen roared into general consumption: acrylic textiles, Plexiglass, polyethylene bottles, polypropylene containers, and "foam rubber" polyurethane toys. Most world-changing of all was transparent packaging, including self-clinging wraps of polyvinyl chloride and polyethylene, which let us see the foods wrapped inside them and kept them preserved longer than ever before.

Within 10 years, the downside to this wonder substance was apparent. *Life Magazine* coined the term "throwaway society," though the idea of tossing trash was hardly new. Humans had done that from the beginning with leftover bones from their hunt and chaff from their harvest, whereupon other organisms took over. When manufactured goods entered the garbage stream, they were at first considered less offensive than smelly organic wastes. Broken bricks and pottery became the fill for the buildings of subsequent generations. Discarded clothing reappeared in secondary markets run by ragmen, or were recycled into new fabric. Defunct machines that accumulated in junkyards could be mined for parts or alchemized into new inventions. Hunks of metal could simply be melted down into something totally different. World War II—at least the Japanese naval and air portion—was literally constructed out of American scrap heaps.

Stanford archaeologist William Rathje, who has made a career of studying garbage in America, finds himself continually disabusing waste-management officials and the general public of what he deems a myth: that plastic is responsible for overflowing landfills across the country. Rathje's decades-long Garbage Project, wherein students weighed and measured weeks' worth of residential waste, reported during the 1980s that, contrary to popular belief, plastic accounts for less than 20 percent by volume of buried wastes, in part because it can be compressed more tightly than other refuse. Although increasingly higher percentages of plastic items have been produced since then, Rathje doesn't expect the proportions to change, because improved manufacturing uses less plastic per soda bottle or disposable wrapper.

The bulk of what's in landfills, he says, is construction debris and paper products. Newspapers, he claims, again belying a common assumption, don't biodegrade when buried away from air and water. "That's why we have 3,000-year-old papyrus scrolls from Egypt. We pull perfectly readable newspapers out of landfills from the 1930s. They'll be down there for 10,000 years."

He agrees, though, that plastic embodies our collective guilt over trashing the environment. Something about plastic feels uneasily permanent. The difference may have to do with what happens outside landfills, where a newspaper gets shredded by wind, cracks in sunlight, and dissolves in rain—if it doesn't burn first.

What happens to plastic, however, is seen most vividly where trash is never collected. Humans have continuously inhabited the Hopi Indian Reservation in northern Arizona since AD 1000—longer than any other site in today's United States. The principal Hopi villages sit atop three mesas with 360° views of the surrounding desert. For centuries, the Hopis simply threw their garbage, consisting of food scraps and broken ceramic, over the sides of the mesas. Coyotes and vultures took care of the food wastes, and the pottery sherds blended back into the ground they came from.

That worked fine until the mid-20th century. Then, the garbage tossed over the side stopped going away. The Hopis were visibly surrounded by a rising pile of a new, nature-proof kind of trash. The only way it disappeared was by being blown across the desert. But it was still there, stuck to sage and mesquite branches, impaled on cactus spines.

South of the Hopi Mesas rise the 12,500-foot San Francisco Peaks, home to Hopi and Navajo gods who dwell among aspens and Douglas firs: holy mountains cloaked in purifying white each winter—except in recent years, because snow now rarely falls. In this age of deepening drought and rising temperatures, ski lift operators who, the Indians claim, defile sacred ground with their clanking machines and lucre, are being sued anew. Their latest desecration is making artificial snow for their ski runs from wastewater, which the Indians liken to bathing the face of God in shit.

East of the San Francisco Peaks are the even taller Rockies; to their west are the Sierra Madres, whose volcanic summits are higher still. Impossible as it is for us to fathom, all these colossal mountains will one day erode to the sea—every boulder, outcrop, saddle, spire, and canyon wall. Every massive uplift will pulverize, their minerals dissolving to keep the oceans salted, the plume of nutrients in their soils nourishing a new marine biological age even as the previous one disappears beneath their sediments.

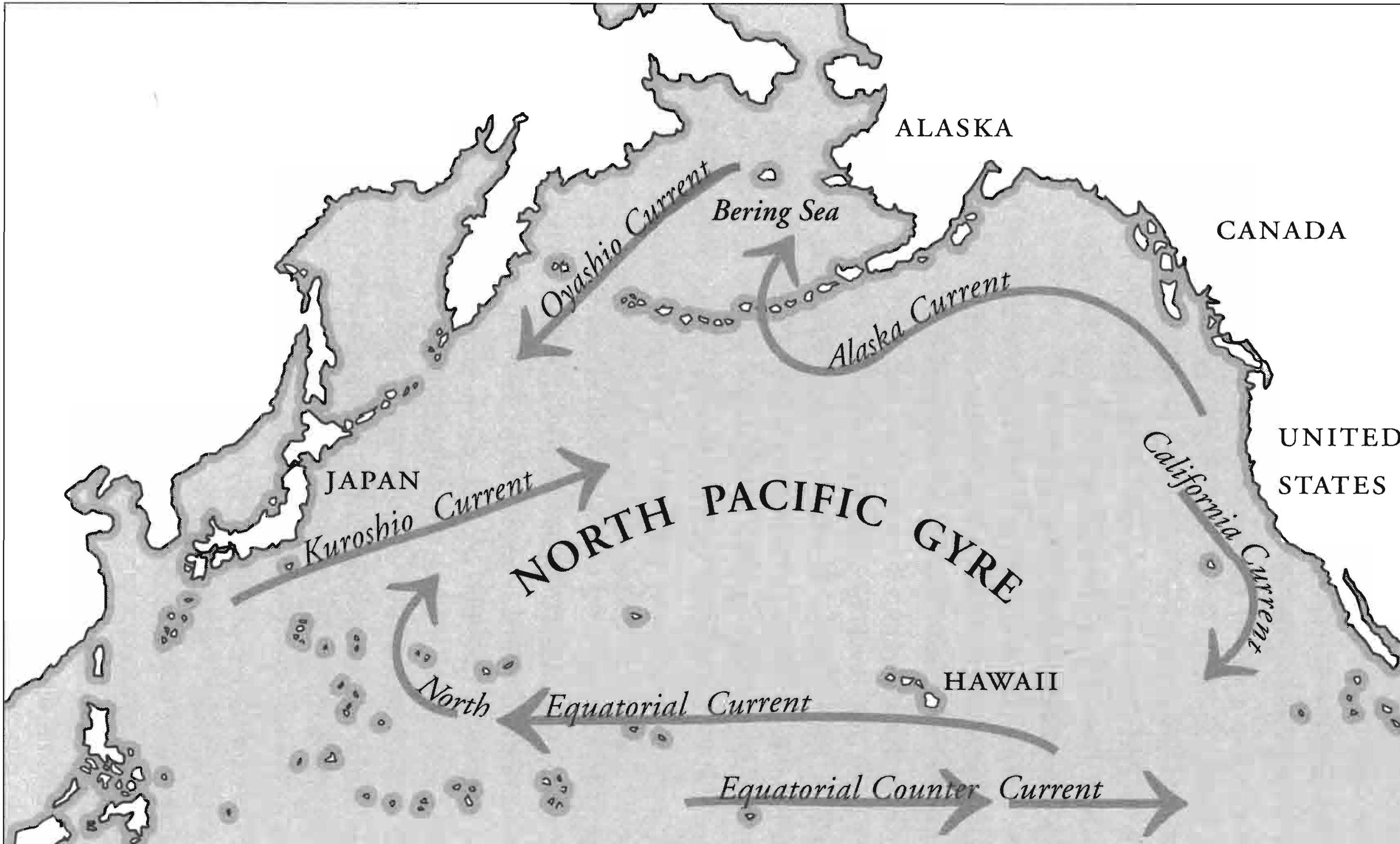
Long before that, however, these deposits will have been preceded by a substance far lighter and more easily carried seaward than rocks or even grains of silt.

Capt. Charles Moore of Long Beach, California, learned that the day in 1997 when, sailing out of Honolulu, he steered his aluminum-hulled catamaran into a part of the western Pacific he'd always avoided. Sometimes known as the horse latitudes, it is a Texas-sized span of ocean between Hawaii and California rarely plied by sailors because of a perennial, slowly rotating high-pressure vortex of hot equatorial air that inhales wind and never gives it back. Beneath it, the water describes lazy, clockwise whorls toward a depression at the center.

Its correct name is the North Pacific Subtropical Gyre, though Moore soon learned that oceanographers had another label for it: the Great Pacific Garbage Patch. Captain Moore had wandered into a sump where nearly everything that blows into the water from half the Pacific Rim eventually ends up, spiraling slowly toward a widening horror of industrial excretion. For a week, Moore and his crew found themselves crossing a sea the size of a small continent, covered with floating refuse. It was not unlike an Arctic vessel pushing through chunks of brash ice, except what was bobbing around them was a fright of cups, bottle caps, tangles of fish netting and monofilament line, bits of polystyrene packaging, six-pack rings, spent balloons, filmy scraps of sandwich wrap, and limp plastic bags that defied counting.

Just two years earlier, Moore had retired from his wood-furniture-finishing business. A lifelong surfer, his hair still ungrayed, he'd built himself a boat and settled into what he planned to be a stimulating young retirement. Raised by a sailing father and certified as a captain by the U.S. Coast Guard, he started a volunteer marine environmental monitoring group. After his hellish mid-Pacific encounter with the Great Pacific Garbage Patch, his group ballooned into what is now the Algita Marine Research Foundation, devoted to confronting the flotsam of a half century, since 90 percent of the junk he was seeing was plastic.

What stunned Charles Moore most was learning where it came from. In 1975, the U.S. National Academy of Sciences had estimated that all oceangoing vessels together dumped 8 million pounds of plastic annually. More recent research showed the world's merchant fleet alone shamelessly tossing around 639,000 plastic containers every day. But littering by all the commercial ships and navies, Moore discovered, amounted to mere




Map of North Pacific Gyre.

MAP BY VIRGINIA NOREY

polymer crumbs in the ocean compared to what was pouring from the shore.

The real reason that the world's landfills weren't overflowing with plastic, he found, was because most of it ends up in an ocean-fill. After a few years of sampling the North Pacific gyre, Moore concluded that 80 percent of mid-ocean flotsam had originally been discarded on land. It had blown off garbage trucks or out of landfills, spilled from railroad shipping containers and washed down storm drains, sailed down rivers or wafted on the wind, and found its way to this widening gyre.

"This," Captain Moore tells his passengers, "is where all the things end up that flow down rivers to the sea." It is the same phrase geologists have uttered to students since the beginning of science, describing the inexorable processes of erosion that reduce mountains to dissolved salts and specks small enough to wash to the ocean, where they settle into layers of the distant future's rocks. However, what Moore refers to is a type of runoff and sedimentation that the Earth had hitherto never known in 5 billion years of geologic time—but likely will henceforth.

During his first 1,000-mile crossing of the gyre, Moore calculated half a pound for every 100 square meters of debris on the surface, and arrived at 3 million tons of plastic. His estimate, it turned out, was corroborated by U.S. Navy calculations. It was the first of many staggering figures he would encounter. And it only represented *visible* plastic: an indeterminate amount of larger fragments get fouled by enough algae and barnacles to sink. In 1998, Moore returned with a trawling device, such as Sir Alistair Hardy had employed to sample krill, and found, incredibly, more plastic by weight than plankton on the ocean's surface.

In fact, it wasn't even close: six times as much.

When he sampled near the mouths of Los Angeles creeks that emptied into the Pacific, the numbers rose by a factor of 100, and kept rising every year. By now he was comparing data with University of Plymouth marine biologist Richard Thompson. Like Thompson, what especially shocked him were plastic bags and the ubiquitous little raw plastic pellets. In India alone, 5,000 processing plants were producing plastic bags. Kenya was churning out 4,000 tons of bags a month, with no potential for recycling.

As for the little pellets known as nurdles, 5.5 *quadrillion*—about 250 billion pounds—were manufactured annually. Not only was Moore finding them everywhere, but he was unmistakably seeing the plastic resin bits trapped inside the transparent bodies of jellyfish and salps, the ocean's most prolific and widely distributed filter-feeders. Like seabirds, they'd mistaken brightly colored pellets for fish eggs, and tan ones for krill. And now God-knows-how-many quadrillion little pieces more, coated in body-scrub chemicals and perfectly bite-sized for the little creatures that bigger creatures eat, were being flushed seaward.

What did this mean for the ocean, the ecosystem, the future? All this plastic had appeared in barely more than 50 years. Would its chemical constituents or additives—for instance, colorants such as metallic copper—concentrate as they ascended the food chain, and alter evolution? Would it last long enough to enter the fossil record? Would geologists millions of years hence find Barbie doll parts embedded in conglomerates formed in seabed depositions? Would they be intact enough to be pieced together like dinosaur bones? Or would they decompose first, expelling hydrocarbons that would seep out of a vast plastic Neptune's graveyard for eons to come, leaving fossilized imprints of Barbie and Ken hardened in stone for eons beyond?

Moore and Thompson began consulting materials experts. Tokyo University geochemist Hideshige Takada, who specialized in EDCs—endocrine-disrupting chemicals, or "gender benders"—had been on a gruesome mission to personally research exactly what evils were leaching from garbage dumps all around Southeast Asia. Now he was examining plastic pulled from the Sea of Japan and Tokyo Bay. He reported that in the sea, nurdles and other plastic fragments acted both as magnets and as sponges for resilient poisons like DDT and PCBs.

The use of aggressively toxic polychlorinated biphenyls—PCBs—to make plastics more pliable had been banned since 1970; among other hazards, PCBs were known to promote hormonal havoc such as hermaphroditic fish and polar bears. Like time-release capsules, pre-1970 plastic flotsam will gradually leak PCBs into the ocean for centuries. But, as Takada also discovered, free-floating toxins from all kinds of sources—copy paper, automobile grease, coolant fluids, old fluorescent tubes, and infamous discharges by General Electric and Monsanto plants directly into streams and rivers—readily stick to the surfaces of free-floating plastic.

One study directly correlated ingested plastics with PCBs in the fat tissue of puffins. The astonishing part was the amount. Takada and his colleagues found that plastic pellets that the birds ate concentrate poisons to levels as high as 1 million times their normal occurrence in seawater.

By 2005, Moore was referring to the gyrating Pacific dump as 10 million square miles—nearly the size of Africa. It wasn't the only one: the planet has six other major tropical oceanic gyres, all of them swirling with ugly debris. It was as if plastic exploded upon the world from a tiny seed after World War II and, like the Big Bang, was still expanding. Even if all production suddenly ceased, an astounding amount of the astoundingly durable stuff was already out there. Plastic debris, Moore believed, was now the most common surface feature of the world's oceans. How long would it last? Were there any benign, less-immortal substitutes that civilization could convert to, lest the world be plastic-wrapped evermore?

That fall, Moore, Thompson, and Takada convened at a marine plastic summit in Los Angeles with Dr. Anthony Andrady. A senior research scientist at North Carolina's Research Triangle, Andrady is from Sri Lanka, one of South Asia's rubber-producing powers. While studying polymer science in graduate school, he was distracted from a career in rubber by the surging plastics industry. An 800-page tome he eventually compiled, *Plastics in the Environment,* won him acclaim from the industry and environmentalists alike as the oracle on its subject.

The long-term prognosis for plastic, Andrady told assembled marine scientists, is exactly that: long-term. It's no surprise that plastics have made an enduring mess in the oceans, he explained. Their elasticity, versatility (they can either sink or float), near invisibility in water, durability, and superior strength were exactly why net and fishing line manufacturers had abandoned natural fibers for synthetics such as nylon and polyethylene. In time, the former disintegrate; the latter, even when torn and lost, continue "ghost fishing." As a result, virtually every marine species, including whales, is in danger of being snared by great tangles of nylon loose in the oceans.

Like any hydrocarbon, Andrady said, even plastics "inevitably must biodegrade, but at such a slow rate that it is of little practical consequence. They can, however, photodegrade in a meaningful time frame."

He explained: When hydrocarbons biodegrade, their polymer molecules are disassembled into the parts that originally combined to create them: carbon dioxide and water. When they *photodegrade,* ultraviolet solar radiation weakens plastic's tensile strength by breaking its long, chain-like polymer molecules into shorter segments. Since the strength of plastics depends on the length of their intertwined polymer chains, as the UV rays snap them, the plastic starts to decompose.

Everyone has seen polyethylene and other plastics turn yellow and brittle and start to flake in sunlight. Often, plastics are treated with additives to make them more UV-resistant; other additives can make them more UV-sensitive. Using the latter for six-pack rings, Andrady suggested, might save the lives of many sea creatures.

However, there are two problems. For one, plastic takes much longer to photodegrade in water. On land, plastic left in the sun absorbs infrared heat, and is soon much hotter than the surrounding air. In the ocean, not only does it stay cooled by water, but fouling algae shield it from sunlight.

The other hitch is that even though a ghost fishnet made from photodegradable plastic might disintegrate before it drowns any dolphins, its chemical nature will not change for hundreds, perhaps thousands of years.

"Plastic is still plastic. The material still remains a polymer. Polyethylene is not biodegraded in any practical time scale. There is no mechanism in the marine environment to biodegrade that long a molecule." Even if photodegradable nets helped marine mammals live, he concluded, their powdery residue remains in the sea, where the filter feeders will find it.

"Except for a small amount that's been incinerated," says Tony Andrady the oracle, "every bit of plastic manufactured in the world for the last 50 years or so still remains. It's somewhere in the environment."

That half-century's total production now surpasses 1 billion tons. It includes hundreds of different plastics, with untold permutations involving added plasticizers, opacifiers, colors, fillers, strengtheners, and light stabilizers. The longevity of each can vary enormously. Thus far, none has disappeared. Researchers have attempted to find out how long it will take polyethylene to biodegrade by incubating a sample in a live bacteria culture. A year later, less than 1 percent was gone.

"And that's under the best controlled laboratory conditions. That's not what you will find in real life," says Tony Andrady. "Plastics haven't been around long enough for microbes to develop the enzymes to handle it, so they can only biodegrade the very-low-molecular-weight part of the plastic"—meaning, the smallest, already-broken polymer chains. Although truly biodegradable plastics derived from natural plant sugars have appeared, as well as biodegradable polyester made from bacteria, the chances of them replacing the petroleum-based originals aren't great.

"Since the idea of packaging is to protect food from bacteria," Andrady observes, "wrapping leftovers in plastic that encourages microbes to eat it may not be the smartest thing to do."

But even if it worked, or even if humans were gone and never produced another nurdle, all the plastic already produced would remain—how long?

"Egyptian pyramids have preserved corn, seeds, and even human parts such as hair because they were sealed away from sunlight with little oxygen or moisture," says Andrady, a mild, precise man with a broad face and a clipped, persuasively reasonable voice. "Our waste dumps are somewhat like that. Plastic buried where there's little water, sun, or oxygen will stay intact a long time. That is also true if it is sunk in the ocean, covered with sediment. At the bottom of the sea, there's no oxygen, and it's very cold."

He gives a clipped little laugh. "Of course," he adds, "we don't know much about microbiology at those depths. Possibly anaerobic organisms there can biodegrade it. It's not inconceivable. But no one's taken a submersible down to check. Based on our observations, it's unlikely. So we expect much-slower degradation at the sea bottom. Many times longer. Even an order of magnitude longer."

An order of magnitude—that's 10 times—longer than what? One thousand years? Ten thousand?

No one knows, because no plastic has died a natural death yet. It took today's microbes that break hydrocarbons down to their building blocks a long time after plants appeared to learn to eat lignin and cellulose. More recently, they've even learned to eat oil. None can digest plastic yet, because 50 years is too short a time for evolution to develop the necessary biochemistry.

"But give it 100,000 years," says Andrady the optimist. He was in his native Sri Lanka when the Christmas 2004 tsunami hit, and even there, after those apocalyptic waters struck, people found reason to hope. "I'm sure you'll find many species of microbes whose genes will let them do this tremendously advantageous thing, so that their numbers will grow and prosper. Today's amount of plastic will take hundreds of thousands of years to consume, but, eventually, it will all biodegrade. Lignin is far more complex, and it biodegrades. It's just a matter of waiting for evolution to catch up with the materials we are making."

And should biologic time run out and some plastics remain, there is always geologic time.

"The upheavals and pressure will change it into something else. Just like trees buried in bogs a long time ago—the geologic process, not biodegradation, changed them into oil and coal. Maybe high concentrations of plastics will turn into something like that. Eventually, they will change. Change is the hallmark of nature. Nothing remains the same."