# The Unfinished Miracle: How Plastics Came to Be Lost at Sea

by

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ABSTRACT

Plastic trash is an increasingly significant source of pollution in the world's oceans. In some remote ocean regions, it is aggregating by the ton. This thesis investigates plastic trash as an emerging marine contaminant, with a specific focus on: the history of plastic trash in the ocean; areas of aggregation; potential sources; remediation efforts; behavior of the material in terms of degradation in the marine environment; impacts to sea life and marine ecosystems; and scientific research, both ongoing and planned, that will attempt to determine further potential impacts to marine ecosystems and human health.

The second part of this inquiry provides a brief explanation of what plastics are, the history of plastic polymer development and the significance of the material's incredible contributions to society. It explores briefly the growing social backlash against plastic as a result of the publicized impacts of plastic ocean trash, and concludes with an argument, which states that the problem of plastic marine pollution is not due to the nature of the material itself, but rather lies in the ways we have chosen to use it.

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# THE UNFINISHED MIRACLE
How plastics came to be lost at sea

by Amanda Rose Martinez

The drive out to Kamilo Beach on the southeast shore of the Big Island of Hawaii is not for the weak-willed. Bordering the rural Ka'u District, the crescent-shaped beach lies in the 13,680-foot shadow of Mauna Loa, one of the island's two active volcanoes. South Point Road is the only street on the map that comes close to Kamilo, but about six miles from shore, the pavement ends. A rugged dirt path, guarded by a pack of longhorn steers, stretches through the next three miles of private ranchland. Here the road fades to mere suggestion—two strips of matted grass, spaced tire-width apart. Another mile in and anything resembling a road disappears completely, replaced by a rust-colored moonscape of fist-sized volcanic rock. Although a seemingly infinite swath of Pacific Ocean engulfs the horizon, from here it still takes three hours to reach the coast.

In April of 1868, lava flow from the erupting Mauna Loa blanketed the region on its way out to sea. Mounds of its cooled remnants shatter like broken glass beneath the tires of our jeep 4x4, forcing us to creep along at an excruciating two-miles-per-hour. Closer in, massive logs, bleached bone-white from the sun, start to appear. Pulled ashore by the powerful tides at Kamilo, they stage a stark contrast against the black pumice terrain. Finally, the shore comes into view. Strong winds howl at the water's edge, where smooth tongues of blackened lava extend into the surf. But the strangeness of this scene is upstaged by another feature of the beach. Miles from the nearest person or dwelling, Kamilo's high tide line is covered with trash.

A construction worker's hard hat, water bottles, lighters, busted buckets, chunks of insulation foam, floats, toothbrushes, shoes, toys, and countless bottle caps create a riot of color. There are broken laundry detergent bottles and food containers, sections of PVC tubing rival twigs in number, and a faded birthday message is still evident on a spent mylar balloon. A few chunks of rusted metal can be spotted, along with one or two glass bottles, but most of the trash is plastic.

Above the high tide line sits a tangled mass of fishing nets and rope the size of a small car. With its mash of bright blues, greens, yellows and oranges, it looks almost comical, like an enormous, amorphous muppet. Closer inspection reveals a foul stench, a mix of seawater-logged polyethylene net and rotting marine life. With such an assortment of recognizable objects, it's easy to overlook the smaller plastic fragments. But then you start to notice them—the silver dollar-sized pieces with perfectly round edges, shaped by surf, the confetti-sized shards in every color, the particles on par with sand grains—and realize they're everywhere. What wind and wave action has traditionally done for glass, on this remote beach in the middle of the Pacific Ocean, it has begun to do for plastic. On Kamilo, the concept of sand is being redefined.

"What's out there now," said Noni Sanford, a Big Island resident, "that's nothing. When we first started cleaning, there were tons of it, I mean literally tons." Sanford has a wide face and a kind smile, and wears her long, gray hair pulled into a braid that stretches the length of her back. She and her husband run the volunteer fire department in Volcano Village, a sleepy town located about forty-five miles north of Kamilo and directly adjacent to the island's other smoldering volcanic caldera, Kilauea. When I visited the town one day in early January, a thick, volcanic fog was rolling through. As Sanford and I talked in Volcano's small firehouse, the fog's droplets of sulfur dioxide gas were enough to make us cough.

In 1960, when Sanford first made the trek to Kamilo as a child, there was no trash. She recalls driving down with her father and some ranchers in "great, big, old farm trucks" to gather driftwood to build a new barn. All the trees around here are kind of twisted and gnarly, Sanford explains. The tides at Kamilo, which literally translates from Hawaiian to mean "twisting of currents," bring in easy-to-cut, timber logs from as far away as the Pacific Northwest. The island's Polynesian settlers used to carve canoes out of them. Fifty years ago, the only things Sanford remembers seeing were the logs and some glass fishing floats. Fifteen years passed before Sanford had the chance to return to Kamilo, but when she did, the sight that awaited her, she says, took her breath away.

"It was buried in rubbish," Sanford said. "The stuff was piled eight to ten feet deep on one end of the beach." It was mainly fishing gear, but there were a lot of household items. Most everything was plastic. It was obvious to Sanford that the trash hadn't come from Hawaii. "You saw how hard it is to get out there," she said. "You'll get fishermen who go because it's one of the last places that isn't fished out." They'll camp for a few nights and maybe leave some litter behind, but this trash was different. Besides the sheer quantity, it was faded and battered and much of it displayed Japanese characters. It had been carried by the ocean from someplace else, and considering that the Hawaiian Islands are located just shy of twenty-four hundred miles from the nearest land mass, that "someplace else" had to be pretty far away.

"Well at first it was exciting," said Sanford, an avid beachcomber. "Just the idea of what you might be able to find, something neat. But then you see it floating in the water and you kind of crash. It's like: 'Oh shit. What are we going to do with this?' "

From that moment, Sanford and her husband, Ron have been on a mission. The couple's initial attempts to clean Kamilo's trash by themselves, (overwhelming and futile, Sanford said), led them to recruit volunteers for modest, but consistent cleanups. They recently purchased a bright orange Mercedes Benz Unimog—a truck that resembles a Tonka toy and is used to pull railway cars—for the express purpose of dragging multi-ton, derelict net bundles out of the encroaching surf.

In 2003, the Sanfords joined forces with the Hawaii Wildlife Fund, a local conservation nonprofit, which staged the first large-scale cleanup of Kamilo that same year. For two days, one hundred and fifty volunteers filled two dump trucks that took turns driving to the landfill. When they finished, they had cleared fifty tons of junk. The Fund has since held methodical cleanings on a nine-mile stretch of debris-prone coastline that begins just northeast of Kamilo and extends to the island's southernmost tip. After seven years, the Fund has helped rid the region of one hundred and twenty tons of trash.

But it just keeps coming. Each year, the Fund estimates, between ten and twenty tons of fresh trash wash ashore.

Clear across to the other end of the Hawaiian Archipelago, fifteen hundred and twenty miles away, a team of NOAA divers are engaged in their own Sisyphean struggle with ocean trash. Every year, sixteen divers live on a ship for several weeks and spend their days painstakingly dislodging all manner of plastic junk from the delicate reefs of the ten islands, atolls and submerged seabanks that comprise the Northwestern Hawaiian Islands.

The islands, uninhabited by humans, are an oceanic wilderness. Home to seven thousand species, they boast some of the world's largest seabird colonies, as well as one of the world's few remaining intact coral reef systems, and the U.S. government would like to keep it that way. A permit is required to visit the islands, which were designated as a marine national monument in 2007, but these permits take months to clear and are only granted for research and conservation projects. There are no commercial flights to the islands and chartered flights cost thirty thousand dollars per round trip.

In the early 1990s, marine biologists noticed something unusual; fishing nets, which Hawaiian commercial fisheries are banned from using, were washing into and getting caught up within the islands' reefs. Junk was piling up on beaches with no human footprints—styrofoam chunks, cathode-ray tubes, light bulbs and other consumer products, mostly made of plastic. The biologists noted that some of the junk was harming sea life. Monk seals would surface, wrapped in net fragments or be spotted with plastic cups lodged on their snouts, and albatross carcasses revealed stomachs full of plastic pieces. In 1996, NOAA with help from the U.S. Coast Guard, launched an intensive program to clear the islands' of their debris backlog. Over the next decade, divers removed nearly five hundred and eighty-six metric tons of trash from the area.

Ninety-nine per cent of the divers' work is done via free dive. Scuba gear magnifies the already high risk of entanglement in the debris. Given the low light thirty feet down, a diver can easily become ensnared in webs of hair-thin, clear, monofilament fishing line. To prepare for such situations, all divers undergo a rigorous training program back on Oahu. Blindfolded, submerged and entangled in a net, they have to free themselves.

Susie Holst, a NOAA diver during the 2004 and 2005 field seasons reassured me that over the course of four months, "you actually develop a really significant breath hold." If you're being towed behind the boat, you can usually hold your breath for over two minutes, Holst explained. Diving down thirty feet to tie a rope to some piece of trash, which can then be hauled to the surface, is also not too taxing. "It's when you're exerting yourself to carry something heavy or cutting a net free from the reef that your time really drops."

It's worth the risk though, Holst says, when compared to the devastation multi-ton masses of fishing gear inflict on the reefs. "Basically, it's like a tumbleweed," she said. Pieces of net catch on the coral heads and, propelled by the currents and wind and their own sheer bulk, they can rip the coral heads right out of the reef, creating a path of devastation that Holst compares to the wake of a tornado. Eventually, the whole thing gets so heavy, it sinks, and becomes an artificial reef on the ocean floor. Young fish, moray eels, and little lobsters take up residence in it, which isn't a problem, until their predators—sea turtles or seals that need to breathe air—come seeking a meal. They get their heads caught in a net loop and drown. "Then it's just a giant, baited mousetrap," Holst said. In 2006, the program switched to maintenance mode, but continues to dispose of the more than fifty-two tons of debris that bombard the islands each year.

What Sanford and the NOAA divers didn't know when they first began to wage battle against the unrelenting tide of plastic trash on their respective beaches is that they were not alone. Beaches all over the world have been experiencing an influx of trash from the sea. The problem is that most of the trash is made of plastic, which doesn't biodegrade. As a result, it has begun to pile up. Scientists have already discovered giant convergence zones where plastic is amassing in two of the world's oceans, and they have reason to believe that other oceans may have similar zones as well. It now appears that, since plastic production began to ramp up in the 1950s, a steady stream of plastic trash has been making its way into the sea.

Plastic was invented to be a panacea to manufacturing. As the first entirely manmade material, it was engineered to solve our greatest product design challenges and make irrelevant the fact that our natural resources are finite. But the creators of plastic had never lived in a world with anything like it. They could not and did not anticipate that this miracle material, once discarded, would last forever.

Hawaii declared ocean trash to be a serious and escalating issue for the entire state after a NOAA-helicopter survey in 2006 revealed over seven hundred sites of debris accumulation, affecting every island in the chain. Perhaps the most pressing issue Hawaii faces is how to get rid of all the trash. The nets, at least, can be recycled. Since 2002, a handful of Hawaiian companies have worked in concert, donating their resources and time to create a statewide "Nets-to-Energy" program. When its net debris pile hits about seven tons, the Hawaii Wildlife Fund pays to have the nets fumigated. (This is to ensure that the island's geckos, cockroaches and coqui frogs aren't transported as invasive species to Oahu.) The nets are then loaded into a fourteen-ton container, donated by a local transport company, and shipped to Honolulu Harbor. After being chopped up into eighteen-inch chunks at a nearby steel mill, the net scraps are burned at one of the city's power plants. Since the program's inception, its combusted nets have generated enough energy to power two hundred and forty-five family homes for a year.

Disposing of non-net trash, however, is more of a problem. At Kamilo's most recent clean-up in September of 2009, volunteers collected nearly one ton of non-net trash. Megan Lamson, who coordinates the Fund's beach cleanups, says they try to recycle as much as possible, but cites the state's recycling program as being "very, very picky." For instance, they won't take plastic bottles without labels or anything that's been faded by the sun. "They basically can't recycle marine debris," she said.

The rest gets dumped at the east side landfill in South Hilo, one of only two landfills on the island. Mike Dworsky, head of the Big Island's Solid Waste Division, says the forty-acre east side landfill is almost filled. "The trash that's there is about ninety-six-feet high above the surrounding terrain," he said. "It's got about six to eight more years on it." The county is currently debating whether to impose a two-dollar tax on every garbage bag its residents throw out to try and slow the flow of trash.

As the islands struggle to manage their own mounting waste, they must also somehow accommodate the tons of junk that the ocean brings ashore every year. "Hopefully, in the future, we can do something else with it," Lamson said. "But right now, this is our only option."

Why are the Hawaiian islands being inundated with so much trash from the sea? The answer amounts simply to geographic misfortune. Isolated in the middle of the North Pacific ocean, the islands are located along the southern edge of an oceanic feature called the North Pacific subtropical gyre.

A subtropical gyre forms primarily due to wind patterns. Heat from the sun warms the air at the Equator, which then begins to rise and move toward the poles. As the heated air encounters the cooler air emanating from the poles, it sinks, creating a region defined by its stillness. The air here is stagnant; there is little to no wind. Clouds rarely form, and as a result, there is very little precipitation. In the Northern Hemisphere, these regions of stillness occur within a latitude band centered at roughly thirty degrees north. Trace the band across the continents and you'll encounter the world's deserts.

In this way, the North Pacific subtropical gyre is like an oceanic desert, except that when the descending air reaches the ocean, the rotation of the Earth causes the air to slowly start spinning in a clockwise motion. Just like a disc jockey's finger pulls on the surface of a record, the spinning air tugs on the ocean's surface, and it too starts to spin. Four main currents—the North Pacific, California, North Equatorial and Kuroshio currents—feed the gyre, percolating slowly within it. Sailors have long steered clear of the region. Nicknamed the "horse latitudes" or "the doldrums," the becalmed waters have a reputation for stalling sailboats and draining the fuel reserves of motor-equipped vessels in a region of the ocean that is just about as far away from civilization as one can get.

But sailors now have another reason to keep out.

In August of 1997, Charles Moore, was sailing from Honolulu to his home in Long Beach, California in his aluminum-hulled catamaran, *Alguita*. He had just won third place in the prestigious Transpacific Yacht Race, and feeling unrushed and a bit adventurous, Moore decided to cut through the southern edge of the North Pacific subtropical gyre—an area he had always avoided. What he saw as he veered north into the gyre rocked him to his core.

"As I gazed from the deck at the surface of what ought to have been a pristine ocean, I was confronted, as far as the eye could see, with the sight of plastic," Moore wrote in an op-ed piece that appeared last year in Arts and Opinion Magazine. It took him a week to sail through the gyre. It didn't matter the time of day, Moore told me, "when I would come on deck and just survey the horizon, I would see something floating by." He listed a few things—bottle caps, a toothbrush, a net fragment, plastic particles. All were the same manner of junk that rushes the shores of Hawaii.

"What bothered me most was that we were in the remotest part of the ocean," Moore said. "We were as far from land as you can get anywhere on earth and still we couldn't get away from this stuff. Why are we seeing it out here?"

Most of the trash in the gyre is now thought to originate on land. Oceanographers believe that if you toss a plastic bottle off the coast of any of the Pacific Rim countries in the northern hemisphere, one of the four major currents that feed the gyre will likely deposit it there. As the currents bring new water in, the old water sinks, but the plastic trash floats. The new water adds more floating trash, and it all begins to accumulate in a massive, convergence zone that begins about a thousand miles off the coast of California. It has since been dubbed the "Great Pacific Garbage Patch," or as Moore is fond of describing it: "a giant toilet bowl that never flushes."

The percolating trash can persist in the gyre for years, but changes in climate and random eddy currents will occasionally offer an escape; they push trash out of the gyre, at which point it either gets swept back in or goes careening for the nearest coastline, which, in this case, belongs to Hawaii, roughly eight hundred miles south. The reigning metaphor casts the Hawaiian islands as eighteen teeth of a crooked comb that catch the gyre's junk.

Moore, sixty-two, grew up in Long Beach. He's ridden the ocean's waves in some form all his life—first on his father's boat as a young observer, then as an avid surfer, sailor and, for the last fifteen years, captain of the fifty-foot *Alguita*, which resides in a narrow boat slip, across the street from Moore's childhood home where he still lives. But as his relationship with the sea has grown, so has Moore's awareness of and discontent with what he calls "the deterioration of the marine environment."

"Before I even built my boat, I was starting to think plastic debris was becoming the most common surface feature on the ocean," he said. "You might see whales, you might see dolphins, but you're sure to see a piece of trash out there."

In the early 1990s, Moore retired from a twenty-five-year career in woodworking and furniture restoration, (As we sit at the small, rectangular wooden table in *Alguita*'s tiny cabin, Moore points to an inlay of seaweed in the table's center. "I did this," he said). He had *Alguita* built as a research vessel, and, in 1994, founded the Algalita Marine Research Foundation. He made his first foray into marine conservation, monitoring chemical pollutants for the California State Water Resources Control Board, but the plastic in the gyre so disturbed Moore that, upon his return, he shifted the foundation's focus exclusively to explore the sea's burden of plastic trash.

Moore is not a scientist by training, but, as he argues, by necessity. After that first experience, he was anxious to return to the gyre to get a handle on just how much junk was accruing out there—something that no one was studying at the time. He'd seen so much plastic, he said, that he was convinced he'd be tracking the party responsible for dumping it. Moore's plan was to string a half-inch mesh net between *Alguita*'s two hulls, and catch the plastic that way. But a friend of his, oceanographer Curtis Ebbesmeyer, who'd been studying the breakdown of plastic at sea, recommended that he bring along a net with a much finer mesh for smaller plastic pieces. "He was the one who thought that the plastic was being spit out from the gyre," Moore said.

Taking the advice, Moore borrowed a manta trawl, which, used for catching plankton, consists of a net with mesh measuring three hundred and thirty-three microns, (smaller than the holes in a t-shirt). Two wings extend out from each side of the net's mouth, which allow it to float, skimming the water's surface.

In August of 1999, Moore and a small crew headed back out to the gyre. On the way there, Moore decided to test out the manta net. "Just to practice, we threw it over the side and couldn't believe all the plastic that was in the first trawl," he said. "We were still a good five hundred miles from the site." In all, Moore used the manta net to take eleven trawl samples from random sites within what he had calculated to be the gyre's center. Trawls were conducted both during the day and at night, and for each one, the net was dragged for between three and twelve miles.

The results from the expedition, which were published in the December 2001 issue of the peer-reviewed journal Marine Pollution Bulletin, shocked the scientific community. The samples contained a total of 27,698 pieces of plastic, collected from the sea surface. Although plankton outnumbered plastic in abundance, Moore found that plastic outweighed the plankton by a ratio of roughly six to one.

Since that first cruise, Moore has returned to the gyre eight times to do additional research. When not at sea, he aggressively pursues a public awareness and education campaign about plastic pollution with a small, but devoted staff. Initially, Moore fielded criticism from scientists, who strongly disapproved of his tendency to exaggerate the gyre's junk when describing it to media outlets. Headlines ran with the false image of floating, plastic-trash islands twice the size of Texas in the middle of the Pacific.

In truth, the gyre's junk is much more diffuse. It doesn't form any sort of solid structure on which a person could walk. The majority of it exists as minute plastic fragments that appear as confetti or even a fine dust to someone looking over the side of a boat. This is why there are no satellite pictures. Also, no one has been able to measure the boundaries to which the trash extends, given the enormous challenge presented by the gyre's immensity and constant movement. Moore has since settled on the more accurate, but still disquieting metaphor of a thin plastic soup that stretches for thousands of miles. While some scientists may remain wary of Moore, questioning the accuracy of his research, no one denies that Moore and his foundation have possibly, single-handedly implanted the issue of the ocean's growing plague of plastic trash in the public consciousness and galvanized a community of scientists and advocates toward further research.

Moore has curly, salt-and-pepper hair, big blue eyes and a tinge of rasp to his voice. In moments of repose, his face equilibrates to a solemn expression, perhaps from so many years of fighting to publicize and comprehend the extent of such a redoubtable foe. But his eyes fire up and his speech accelerates as he talks about his latest research. Moore and his crew recently finished a study on the amount of plastic that myctophids, known as lantern fish, are eating in the gyre. Of the six hundred and seventy-two fish the crew collected, more than one-third had plastic in their guts.

"The record holder had eighty-four pieces in it, and mind you, this fish was two-and-a-half inches long," Moore said. What troubles Moore about the lantern fish is that, as one of the most abundant fish in the ocean, they're a staple for the rest of the food web. "In order to reproduce and migrate, these fish have to have fat stores, and the way they get fat stores is to feed frantically," Moore explained. "So this period when they're frantically feeding, taking in all of this plastic, is precisely the time in which they need oils and fats and proteins and energy to complete their lifecycle. They're not getting it with plastic. The population could crash because of this stuff. In fact, I expect it to happen."

Moore continued, citing plastic pollution as an "unrealized, crucial danger" that threatens the entire ocean ecosystem. "A very conservative estimate is that it's doubling every decade," he said. "That's extremely conservative. Everybody should be sampling and analyzing this stuff and then monitoring the consequences because they're huge."

Scientists first discovered plastic in the oceans in the early 1970s. A microbial ecologist named Edward Carpenter published the first study mentioning plastic particles on the ocean surface in the journal Science in March of 1972. Carpenter, a postdoc at the Woods Hole Oceanographic Institution at the time, was on a research cruise in the western North Atlantic, culling the sea surface for microbes. Each time he pulled up his net, it contained plastic. In all, Carpenter took eleven net tows, covering just over eight hundred miles of ocean. He found plastic pieces in every one, and, after sorting and counting them, concluded that, on average, thirty-five hundred plastic particles were present in every square kilometer of seawater.

That may not have amounted to much. It's roughly the equivalent of finding three particles on a football field, thirty feet wide. But the emphasis of Carpenter's article was on how widespread the particles were and how strange it was that any square kilometer seemed to reliably contain them. Carpenter's conclusion was a prediction that if something wasn't done to identify and resolve the plastic's source, the problem was certain to increase. He couldn't have been more prescient; since Carpenter's cruise, according to a report compiled by more than sixty scientists and issued last June by The Royal Society: "plastics have been found on the seabed of all seas and oceans across the planet."

Where is all of this plastic coming from? Some of it can be traced to ships that inadvertently lose their cargo or intentionally dump their plastic trash at sea, although both of these acts are illegal. On December 31, 1988, a law came into effect under Annex V of the International Convention for the Prevention of Pollution From Ships, better known as MARPOL, (short for marine pollution), that banned the disposal of plastics, anywhere at sea. Currently, one hundred and thirty-six countries responsible for nearly ninety-eight per cent of the world's shipping traffic have agreed to adhere to the law. The law, however, has been largely labeled a casualty of good intentions for two reasons. The first is its exemption of the "accidental loss of synthetic fishing nets," which account for a substantial amount of the plastic pollution found at sea. The second is the near impossibility of the law's enforcement. A review published in the Marine Pollution

Bulletin claims that, as of 2002, ships were still dumping an estimated 6.5 million tons of plastic per year.

Still, about eighty percent of the trash that ends up in the ocean is thought to come from land. Beach-going litterbugs share some of the blame, but the sources quickly grow larger in scope. Poorly managed landfills in coastal areas can lose their top layer of trash on a windy day. The sewer systems in many coastal cities are achingly simple, functioning on little more than the principle of "gravity flows." A heavy rain can flush the trash from a city's streets, virtually unimpeded, out to sea. And this isn't limited to coastal towns; inland waterways eventually find their way to the ocean. Toss a plastic bottle into the Mississippi River in Memphis and it's going to find its way to the Gulf of Mexico and out into the North Atlantic.

And then there are the hefty deposits made by major storm events. The 2005 hurricane season, which included Hurricane Katrina, scattered an estimated nine million cubic yards of debris over one thousand seven hundred and seventy acres of coastal marsh in the state of Louisiana alone.

It's not that the concept of debris in the ocean is new. The Royal Society report reassures us that: "Natural marine debris of some type has floated on the surface of the global ocean for longer than life itself." Wood, pumice, algae and shells all fall under the heading of this natural and, therein, benign flotsam. It's the composition of modern debris that has scientists worried.

So far, we know of only one way that plastic breaks down in the environment, and that is through a process called photodegradation. Over time, ultraviolet radiation from the sun weakens the long polymer chains that make plastic so strong. It does this by breaking the bonds between the molecules that form the chains, cleaving them into smaller and smaller chains. In the ocean, constant agitation by waves aids in this weathering. The material gets brittle, crumbling into ever tinier pieces. But this is as far as it goes. It doesn't disappear. Its chemical structure persists, and we still call it plastic.

But in the ocean, photodegradation is no guarantee. Only floating plastics are candidates for exposure to the sun's rays. Those that are too heavy or crustacean-encrusted sink, and with no access to the sun's light or heat, remain whole. Evidence of this was spotted recently by a submersible in the Marseilles canyon off the coast of France. Unopened plastic water bottles, perhaps from a shipment lost en route, lie in a heap on the ocean floor, pristine and entombed at a depth of three thousand two hundred and eighty feet.

With natural debris, microbes can be counted on to do the dirty work of disposal in a process called biodegradation. A discarded piece of paper, for instance, can be a microbial feast; the microbes secrete digestive enzymes that break down the paper's cellulose into simple sugars, which they then use for energy. To date, however, we know of no microbes that digest plastic. It's believed that they simply haven't had enough time to evolve a taste for the material. Scientists conjecture as to how long this evolution might take, their answers ranging from hundreds to even thousands of years. But, for the moment, on any timescale relevant to a human life, plastic is here to stay.

The consensus among scientists is that all of the conventional plastic ever made, save a modest quantity that's been incinerated, still exists somewhere within the environment. Since mass production of plastic really started to accelerate about sixty years ago, well over one billion tons have been manufactured. (That's roughly equal to the weight of nineteen thousand Titanic cruise ships.) And while, plastic makes up only about ten per cent of municipal waste, it now accounts for the majority of debris found in the oceans and on shorelines worldwide.

Already this one-two punch of plastic's ubiquity and durability has led to its strange fusion with marine and coastal habitats. Researchers stationed around the world increasingly encounter these synthetic polymer-based perversities. In Micronesia, juvenile coconut crabs live in detergent bottle caps instead of shells, fish make their home in plastic bottles floating in the Gulf of Aqaba near Israel, and, on a remote beach in the Mergui Archipelago of Burma, a mangrove seedling grows up straight through a plastic bag. Fur seal scat found on Macquarie Island near New Zealand contains so much plastic, it comes in bright hues of yellow, green, blue and red. And the Kittiwake, a type of seabird that lives in Northern Denmark, now weaves its nests mainly out of net fragments, plastic foil and rubber bands.

But beyond this subtle infiltration into life and habitat, plastic at sea has taken a gruesome toll on some marine species. A sea turtle biologist recounts watching hundreds of crabs rush a pile of clear plastic liter bottles that had washed up on a beach in Costa Rica. The crabs sought refuge in the bottles, which, filled with water, seemed safe in the cool, dark night. Come morning, he said, the crabs were cooked alive in the heat of the rising sun.

At sea, animals die by ingesting plastic. Sea turtles and certain whale species mistake plastic bags and packaging, floating on the water's surface, for their prey of jellyfish. The bags get lodged in their digestive system, and they starve to death. For other animals—octopuses, seals, dolphins, sharks, fish, seabirds diving under the impression of having spotted a meal—entanglement is their fate. They get trapped within containers or entangled in nets. Those that need air, drown, while the ones that don't, starve.

Still their plight pales in comparison to that of whales that become ensnared in fishing gear. Beginning in the mid-1940s, fisheries traded their ropes and nets made of natural fiber for new gear made of synthetic material like polyethylene. This synthetic gear is stronger and more efficient, but, unlike its natural predecessor, it doesn't biodegrade. It has since become a bane to whales that, because of their large size, are often able to continue swimming, even as they tow, literally, miles of rope and tons of nets, buoys and crab pots behind them. As they tire themselves out, it can be months before the whales die.

Michael Moore, a biologist who studies right whales in the heavily industrialized waters of the North Atlantic, says there is no question in his mind that these entangled animals are in chronic pain. "When you see the upper arm of the flipper of a whale that has been tightly wrapped by rope for...months," he said, "and all of that rope is buried in new bone that has proliferated around it in an attempt to wall it off, it's barbaric."

In 2008, Nikolai Maximenko, a physical oceanographer at the International Pacific Research Center in Honolulu, was studying how currents move across the ocean's surface when he came across newspaper articles mentioning the plastic trash and its ghastly toll on sea life. Right away, he knew that the plastic accumulating in the North Pacific gyre was no coincidence.

At the time, Maximenko and his colleague, Peter Niiler of Scripps Institute of Oceanography, were preparing to publish a very significant paper. It contained the first accurate map of global ocean surface circulation. Before this map, the world's concept of ocean circulation was, at best, speculative—a hasty mosaic of a few centuries worth of geographers' ship drift measurements, regional buoy experiments and anecdotal observations culled from sea captains' logs. What if, Maximenko thought, by using the surface current data from this new map, he could determine how floating plastic debris might move in the ocean?

In early January, I visited Maximenko at the Research Center, which presides over the fourth floor of the Ocean and Earth Sciences building on the University of Hawaii's Manoa campus in Honolulu. Maximenko has sharp blue eyes, a boyish sort of grin and a strong Russian accent. He grew up next to the Black Sea and came to work in Hawaii because, he says, as if it's obvious, it's in the middle of everything. When we met in a conference room at the Center, Maximenko had staged a projector and large screen, and the map was one of the first slides he pulled up.

Continents on the map are grayed out, relevant only as geographic placeholders, but the oceans are alive with color and movement. Black, wavy lines, signaling currents, snake across the oceans' surface. Colors indicate how fast the currents move. A bold red marks the speedy currents at the equator, as well as such swift and strong, offshore currents as the Gulf Stream. A slower yellow then dominates, spreading north and south from the equator, toward the middle of each ocean, where it fades to tamer greens, then blues. Finally, at the center of each ocean, a white spot appears, signifying a near absence of current movement. Vast clusters of the black current lines converge on these spots and peter out. These white spot-convergences, it turns out, correspond to the five major oceanic subtropical gyres in the Indian Ocean, the North and South Atlantic, and the North and South Pacific.

The map, Maximenko explained, was created using satellite data from more than fourteen thousand drifting buoys that had been released from various locations worldwide over the course of twenty years as part of the Global Drifter Program. Each buoy is made up of a small surface float, which houses a transmitter that communicates the buoy's coordinates to satellites. Attached to the buoy is a type of anchor, called a drogue, that maintains the buoy at fifteen meters below sea level, an ideal depth to catch only surface currents.

Buoys were drawn to the gyres in droves, Maximenko said. They'd get stuck there and percolate for a long time. In some cases, the trapped buoys were lost indefinitely, most likely colonized by opportunistic crustaceans whose added weight then caused the buoys to sink out of circulation. He pointed to the big white spot over the North Pacific subtropical gyre. "This is where the debris is," he said. Then he moved his finger an inch or two straight down to Hawaii, directly south of the gyre. "Hawaii is virtually a destination for marine debris from the entire North Pacific." California is lucky, he explained, due to the constant movement of the cool waters, upwelling along its nutrient-rich coast. Throw something off the coast of California, and it's immediately whisked away and out to sea. "This is payback," Maximenko said with a smile, "for having not-so-pleasant, cold water off its beaches. As a result, California beaches are clean."

But knowing that plastic trash was accruing in the exact spot in the North Pacific to which the buoys had flocked raised an interesting question. What if any plastic that finds its way into the ocean eventually ends up circulating in the nearest subtropical gyre? Would this mean that the other four subtropical gyres are amassing plastic as well?

To test this theory, Maximenko designed a model capable of predicting the fate of theoretical plastic particles in the ocean over the course of many years. He used the behavior of the more than fourteen thousand real buoys to calculate the probable paths that a much larger collection of theoretical particles might take. He then spread those theoretical particles evenly across the entire ocean's surface and let the computer model run a series of iterations equal to a thousand years time. The model assumed that wind and current speed would remain constant, and it didn't take into account any degradation, sinking or ingestion of the plastic by sea life. The only way a particle could be removed from circulation was if it touched land.

Maximenko found that after just three years, the theoretical particles start to converge, forming large smears across the center of every major ocean. By year ten, the theoretical particles had made a beeline for each of the five major subtropical gyres, leaving the waters north and south of the gyres mostly clear. Something that surprised Maximenko was how long the particles remained at sea. After a thousand years, forty-four per cent of the particles were still in the ocean.

While the gyres in the South Atlantic, South Pacific and Indian Ocean have yet to be investigated, scientists from the Sea Education Association in Massachusetts recently confirmed that trash is accumulating in the North Atlantic subtropical gyre. In the mid-1980s, the scientists began noticing small pieces of plastic in the samples they were collecting from a region of the North Atlantic that matches up with the North Atlantic convergence zone of Maximenko's model. For over twenty-five years, they tracked the plastic through a series of sixty-one hundred tows, and now have a data set of more than sixty thousand plastic pieces, most measuring one centimeter or less in size. No one is sure yet how large the plastic accumulation zone in the North Atlantic is, but, according to Kara Lavender Law, oceanographer and lead researcher of the study, the concentration of plastic there rivals that of the North Pacific.

Of all the subtropical gyres, Maximenko believes that the one in the South Pacific has the potential to host the largest mass of trash. Looking at the model, the cluster of theoretical particles centered over the gyre there dwarfs the clusters in other oceans, appearing to be at least twice as large. Over one hundred of the real buoys were lost in the South Pacific gyre and never recovered, he said.

With his model projecting plastic sinks in every major ocean, Maximenko is already scoping strategies to remove the trash directly from the open ocean. "It's not obvious to me that picking plastic from the beaches is what we should be doing," he said. "Maybe we should be getting it before it gets to the beaches. You know it's accumulating within the convergence zone. It's a matter of time before it will go from there to here, so why not collect it there?" The answer, he thinks, may lie in autonomous platforms. For instance, he said, "once you know pathways of derelict fishing gear, you don't need to send expensive ships to get them. You can fish for them with something autonomous. And for the same reason that plastics stay in that area most of the time, autonomous platforms would too. It may be very power efficient."

But before solutions can be considered, the larger question looms: whose responsibility would it be to clean this plastic pollution? As it stands, each coastal nation owns the two hundred-mile-wide belt of ocean that surrounds it, called the Exclusive Economic Zone or EEZ. All totaled, the EEZs of the world account for an estimated thirty-eight million square miles of ocean. In the one hundred and one million square miles of ocean that lie beyond these EEZs, no one country has jurisdiction. This principle of "freedom of the high seas" dates back to the colonial landgrab of the seventeenth century. The seas, it was thought, should remain free to everyone and belong to no one. What that means today in terms of the plastic trash aggregating by the ton in the high seas is that no single nation can be held accountable for cleaning it.

In the last few years, a growing legion of scientists has begun to explore the potential of plastic pollution to have wide-ranging impacts on the ocean ecosystem as a whole. For instance, given its extreme hardiness, plastic has proved an excellent mode of transportation to ferry organisms that grow on it, or, as they're known, "hitch-hikers," to far-flung coasts. Breaching the shores of these new environments, the "hitch-hikers" could become invasive species, possibly presenting a crucial threat to endemic biodiversity.

A group of scientists from the British Antarctic Survey discovered such an event in 2003. They found organisms hailing from ten different species hanging onto a piece of plastic strap that washed ashore on Adelaide Island, a remote island in the Antarctic Peninsula. It was previously believed that islands in the Southern Ocean were not at risk from such invasions, simply because no one thought organisms could survive the region's freezing waters. But the plastic enabled these hitch-hikers to endure. Given the size of some of the organisms, the scientists concluded that they may have been afloat for over a year.

The smallest plastic particles, however, may turn out to have the largest consequences. In September of 2008, forty marine scientists and toxicologists from all over the world convened at the University of Washington in Tacoma for the first conference ever devoted to "microplastics," or all plastic pieces measuring five millimeters or less. The smallest particles scientists are currently able to study, given the limits of instrumentation, are about twenty microns, which is about one-fifth the width of an average piece of human hair.

Microplastics enter the ocean in one of three ways. They can be the weathered remnants of larger plastic objects that have broken down from constant assault by sunlight and roiling waves. There is the at-sea spillage of the raw material used in plastic production—white resin pellets similar in size to quail shot. Each year, two hundred and fifty billion pounds of these pellets are manufactured and shipped around the world. The last known source is certain cleaning products that contain small plastic beads. Measuring in size from fifty microns to one millimeter, these beads act as scrubbers, and are found in everything from the abrasive cleansers used to blast dirt from the hulls of ships and airplanes to the exfoliating creams we use in the shower. The membranes of municipal wastewater treatment systems were not designed to filter these microplastics. As a result, they run down drains, unimpeded, and out to sea.

Initial studies have shown that some of the ocean's smaller organisms—filter feeders, like mussels, lugworms, barnacles and amphipods—will take in microplastics by eating, inhaling or absorbing them through their skin. But another characteristic of microplastics has upped the ante on their potential to impact ocean life at every link in the food chain, including people, as seafood consumers.

In 2001, a group of geochemists in Tokyo released a study showing that microplastic particles act like magnets, drawing to them persistent organic contaminants that are free-floating in the ocean, like DDT and PCBs. The oil-based contaminants are attracted to the plastic particles, which are also made from oil. They cling to a particle's surface and can be concentrated up to a million times the rate at which they are found in the ocean.

Some have thought this might be advantageous. Chemical manufacturers used to dispose of DDT and PCBs by dumping them at sea in the hopes that the chemicals would be diluted. That was before DDT and PCBs were identified as probable carcinogens and their production was outlawed by the U.S. Environmental Protection Agency in 1972 and 1979, respectively. Wouldn't it then be beneficial, some have wondered, if plastic trash floating in the ocean was able to collect and store these poisonous chemicals, in a sense, taking them out of circulation and preventing them from harming marine life?

Unfortunately, scientists have discovered that this magnet-like feature of plastic is actually a further detriment. Some of the contaminants it attracts, if left to their own free-floating fates, would safely biodegrade. Once trapped on the surface of a plastic particle, the contaminant's destiny joins that of the plastic. Neither will biodegrade, as the particle continues to amass contaminants. The issue then becomes the repercussions to marine life that ingest, inhale or absorb this particle, which can now be considered a concentrated dose of poison.

Scientists have barely grazed the surface of this issue. In 2008, Hideshige Takada, a geochemist at Tokyo University, ran an experiment in which he fed forty polyethylene pellets each to five streaked shearwater chicks, (a type of seabird). The pellets were laced with PCBs and mixed in with the chicks' regular diet of fish. A control group just got the fish. After one week, the pellet-eaters showed significantly higher levels of PCBs in their fat tissue compared to the control group, whose only source of PCBs came from the fish. Takada's theory is that the oil-based digestive fluids in the stomach coax the PCBs away from the plastic and into the birds' fat tissue.

But Takada and others are now focusing on a different group of contaminants—the chemical additives that are mixed in with plastics during the manufacturing process. These chemicals are crucial in helping plastics to achieve their flexibility and strength, but some, like phthalates and bisphenol A, two of the most widely used additives, can have disastrous effects on the reproductive systems of organisms that are exposed to them. Known as endocrine disruptors, these chemicals mimic hormones in the body. In animal studies, phthalates and bisphenol A have affected reproduction in every species tested. Amphibians, crustaceans and mollusks are particularly sensitive, exhibiting birth and developmental defects at such low exposure levels as those ranging from one nanogram to one microgram. Such levels are commonly found in the environment. The concern is that these chemicals, already in the microplastics, may leach out once inside an organism.

The unanswered questions that scientists face regarding the effects plastic pollution will have on the ocean are complex and immense in scope. They must figure out if and to what extent microplastics bearing these contaminant loads will impact the health of sea life. If an organism at the base of the food web eats these particles, will every successive predator take on a greater contaminant burden? And if we consider ourselves as one of the larger predators, what might this mean in terms of human health for the estimated one billion people globally who depend on fish as their principal source of animal protein?

In a lab at the Scripps Institute of Oceanography in San Diego, Miriam Goldstein, a biological oceanographer, held a pint-sized jar up to the light. The jar contained a manta-tow's worth of sample, taken from the surface of the North Pacific subtropical gyre. As she shook it, the jar's contents—tiny sea creatures and plastic shards, fixed in a formaldehyde solution—danced around like misshapen snow in a strange snow globe.

"You see these branchy dudes?" Goldstein said, pointing to what looked like a miniature fern. "Those are hydroids," a plant-like invertebrate that stings like a jellyfish. "And these little guys here are krill." She pointed to a clump of clear shrimp the size of rice grains, with brown dots for eyes. There were several fragments of plastic in the jar, ranging in size from a couple of millimeters to an inch. They added vibrant color to the animals' mostly beige palette. Some of the flatter, plastic flakes were encrusted with ochre blobs. "Ooh, those are halobates eggs," Goldstein said, "laid by one of the few marine insects. They actually skate along the surface of the water. But since they live in the open ocean, they're hardly studied."

Goldstein, a fourth-year PhD student, is short, with a wily brown bob, a sharp wit, and mirthful, dark brown eyes that dance when she talks about her work. She balks at the tendency of many to cast the gyre as devoid of sea life. "In no way is it dead," she said. "It's just not lush. It's more like a desert. You're going to see animals, but just not herds of them." Instead, Goldstein said, you find specialized life that has evolved to live in a "low-food way," like the many species of zooplankton, the ocean's smallest animals, that she studies. When describing these diminutive organisms, Goldstein has the uncanny ability to infuse them with a larger-than-life sense of wonder, humor and excitement.

"And these guys here have magical poop," she said, pointing out a cluster of half-inch-long, translucent, barrel-shaped, filter feeders called salps. "It's extremely dense, so it sinks fast, making salps big players in carbon sequestration." Other animal waste, she explained, will take weeks or months to reach the ocean floor. With salp poop, it's three days. "Very impressive poop," she said.

Last August, Goldstein was the chief scientist on Scripps' first research expedition to investigate the trash in the North Pacific gyre. The year before, a representative from Algalita had given a lecture at Scripps about the increasing presence of plastic trash in the ocean, which made a big impression on Goldstein and others. "There were so many open questions about the impact on marine life," she said. "We thought we'd go and see." So Goldstein, with several of her colleagues, submitted a proposal to a unique program at Scripps that gives graduate students a chance to compete to run their own research cruises. The proposal won, and suddenly Goldstein found herself at the helm of the *New Horizon*, one of Scripps' oceanographic vessels, guiding a sixteen-person crew of graduate students on a three-week expedition to the gyre.

As chief scientist, Goldstein was responsible for overseeing all ship operations. "The ship went where I told it to," she said, a bit mischievously. But once they reached the gyre, Goldstein was mainly focused on directing what were often grueling, thirty-six-hour days of intense sampling. Their goal, she said, was to locate high-plastic regions and characterize them. "The thing in the ocean is, you can't really say I'm going to measure from this bench to this bench because the water is always moving," Goldstein said. To really characterize a site, they needed to take multiple samples, using several different sampling methods. Plus, she added, ship operations run twenty-four hours a day because some things happen at night. "It was tough on people at times," she said.

The crew deployed three types of tow nets—a manta net, which sieves zooplankton from the water's surface, a bongo net, which filters zooplankton at a depth of two hundred meters, and an Oozeki net, which, with a larger mesh, trawls for small fish, squid and jellyfish from between four hundred and two thousand meters. When they encountered a larger piece of debris, (particularly those hosting hitch-hikers), a couple of crew members would depart the ship in a small, inflatable boat to retrieve it. All the while, the ship continuously monitored the ocean's physical traits, including temperature, salinity, and chlorophyll fluorescence, which serves as an indicator for phytoplankton abundance.

During the ten days they spent in the gyre, Goldstein and her crew collected one hundred and thirty-two samples. Every single one contained plastic. "There was way more than we expected," she said. "Working in the ocean, it can be really hard to find what you're looking for. I mean, I've lost experiments just off the coast and have had a hard time finding them again." Also, Goldstein said, you tend to find things in distinct patches. "You don't expect to find the same thing for thousands of miles. Normally, even for very abundant animals, you're not necessarily going to get them every single time you sample for thousands of miles. The really unusual thing about the plastic is that it was constant. Now there were areas where there was more and there was less, but there was always plastic once we got out past the California Current and into the gyre. We were still in the transition zone when we started getting it…I mean every single tow. And we'd just be putting our net down at random locations."

While her colleagues try to determine what, if any, health effects the plastic might impose on entire populations of zooplankton, fish, whales, and seabirds, Goldstein will focus on plastic's role in transporting hitch-hikers. She lifted another jar to the light; this one was large enough to house a weathered, plastic sports-drink bottle and a segment of half-inch-thick, black tubing. The bottle hosted a crowded colony of gooseneck barnacles, while the tubing appeared draped in a delicate and diaphanous covering of lace—an invertebrate Goldstein identified as bryozoa.

Hitch-hiker species need a hard surface to grow on, and have been flourishing, Goldstein believes, as a result of all the available plastic. "They're like weeds," she said, turning the jar over in her hands. "They'll take advantage of whatever clear space they can, but they're not necessarily the ones you want a ton of…You have all these barnacles that wouldn't have been there and they have to be eating something. So are they eating way more zooplankton from the surface? Are they impacting those populations? We don't know."

To Goldstein, trying to devise solutions for cleaning the plastic trash before fully understanding the extent of the problem is a misguided effort. "We don't even have answers to the most basic questions," she said, ticking off a litany of unknowns: "How much plastic is there and where is most of it? Is it in the middle of the gyre or does it get pushed out to the edges?...What kind of plastic is it?...And how many pieces are what size? Because that's important for understanding its impact on the food web."

Goldstein hopes her and her crew's research will begin to address some of these questions with a scientific rigor that has been lacking in other investigations into the North Pacific gyre's trash. But it's slow-going. Five months after the expedition, they're still in the process of separating the plastic from the samples, a tedious but necessary step before analysis can be done. Some of the samples, Goldstein said, have taken three hours to segregate. At a small lab bench next to cardboard boxes filled with sample jars, a grad student sits hunched over a microscope. As she peers into the lens at a petri dish full of plastic bits and various zooplankton species, she uses forceps to lift out each plastic piece, transferring them to a foil dish, one by one by one…

The realization that plastic trash, in its environmental permanence and potential to harm sea life, is collecting in the oceans, has solicited a variety of reactions from people—all of which stem from frustration. Scientists and sailors describe a pervasive sadness at encountering commonplace refuse in remote ocean areas. They mourn a wilderness lost, while environmental advocates express outrage at an ecosystem increasingly defiled.

But even for people who never set foot on a boat or rarely see the ocean, the idea of plastic junk piling up at sea seems to cross some sort of tolerance threshold in a way that more abstract environmental issues, like climate change and ocean acidification, fail to do. Their reaction is often a combination of loathing for plastic and guilt at having to rely so heavily on the material to function in society. This has resulted in a growing backlash against plastic. At its moderate end are people merely venting their disgust for the material and bemoaning their futile attempts to avoid it, typically via online forums that launch with the phrase: "I hate plastic." At its extreme end are people who stage individual protests, renouncing all use of plastic as best they can.

Beth Terry is one such plastic ascetic. A forty-five-year-old accountant, who lives in Oakland, California, Terry began weaning herself off of plastic in the summer of 2006. A hyper-conscious consumer, Terry eschews all products that come in plastic packaging. She invests countless hours researching plastic alternatives, which she then posts to her blog "Fake Plastic Fish" for the benefit of other would-be plastic abstainers. And when one of what Terry calls her "durable plastic goods," such as her computer or hair dryer, breaks, she goes out of her way to have it repaired, an effort that often involves tracking down obscure parts from faraway manufacturers. But most of all, Terry says, she's reduced her overall consumption. Her total plastic waste in all of 2009, carefully tallied and weighed, totaled 3.7 pounds—about four per cent of the U.S. average per capita.

What motivated Terry to her plastic-free commitment amounts to little more than a photo she came across online. It depicted an albatross carcass, lying on a beach, with its stomach cavity exposed. It was filled with bottle caps, toothbrushes and lighters, among other plastic chunks. She'd seen tragic photos of animals suffering before, (baby seals being clubbed or polar bears stranded on ice floes, she said,) but this one was different. Her reaction to the photo may shed insight as to why the general public responds so strongly to plastic trash at sea as compared to other environmental problems.

"What I saw inside that bird was stuff that I had inside my house," Terry said. "It hadn't been killed because of something evil that someone was doing. That bird was killed just by our everyday routine and unconscious activities." Terry read the article accompanying the photo, which mentioned the plastic accumulating in the North Pacific and its potential to concentrate toxic chemicals. "It made me think, 'I wonder if we can stop doing this,' " she said. "And I decided to see if I could...But really it was that picture. It just totally shocked me."

Still, in spite of all of her effort, Terry admits, it is impossible to avoid plastic completely. Things like her car, computer and cell phone are always going to be a problem. And then there's the matter of her toothbrush. She uses one made of recycled plastic that can be mailed back to the company for further recycling. But as far as Terry knows, no non-plastic alternative for the toothbrush exists.

In the early 1940s, to the average member of the middle class, a plastic toothbrush was a godsend. Just a decade earlier, most people cleaned their teeth by using a rag to rub them with an abrasive, such as salt or baking soda. The toothbrush, although it had been invented in the late 1850s, was expensive, and therein, considered a luxury available only to the rich. Its handle was made of animal bone and boar hair served as its bristles. It wasn't until 1938, when DuPont released a version made entirely out of plastic, that the toothbrush became affordable to most of society. Its handle was made of a type of plastic, derived from wood, called celluloid and its bristles were made of nylon, a plastic fiber. These synthetic materials enabled the new toothbrush to be sold at a fraction of the price of the old.

At the time, plastic consumer goods were increasingly filling store shelves, and plastic was being heralded as a novel, "miracle material," set to revolutionize society. But what exactly was the excitement for this new material? The basic principle behind plastic design is simple. All plastics are polymers, with "poly," meaning many and "mer," referring to units. These units, which primarily consist of carbon and hydrogen molecules, are connected together repeatedly to create a chain.

Many polymers in fact occur in nature, such as the cellulose found in plant matter and the collagen that helps to build our cartilage, skin and hair. But when natural polymers form, their chemical make-up is directly influenced by variations in their environment. A prolonged drought or a sudden cold snap in spring can threaten the integrity of a tree's cellulose, while our collagen grows at the mercy of such variables as our stress, nutrition and exposure to sunlight. Some of the first plastics were actually based on natural polymers, but when it came to manufacturing consumer goods where uniform quality and high performance were the goal, such irregularities in natural polymer formation presented a real challenge. As a result, chemists modified these natural polymers with chemicals to improve their performance.

Take pure cellulose, for instance. If you heat it, it burns. But in 1868, inventor John Wesley Hyatt mixed cellulose with nitric acid and camphor, a type of tree sap, to get a material that melted when heated. It could then be molded into any form, which hardened when cooled. Hyatt called this semi-synthetic polymer, celluloid, which, as the story goes, he developed as a stand-in for ivory. At the time, elephant tusks were in high demand for piano keys, brush and knife handles, denture sets and billiard balls. A credible ivory doppelganger, celluloid not only relieved the pressure on elephant populations, but could also be made to mimic tortoiseshell, marble and textile stitching.

Celluloid became wildly popular, but unfortunately for Hyatt, another disadvantage of relying on natural materials to make goods soon became apparent—their limited quantity. The camphor used to make celluloid came from a tree that only grew in China, Japan and Taiwan. By 1900, rampant deforestation had left only a few groves standing in Taiwan and the price of camphor rose considerably, signaling the demise of celluloid's manufacturing dominion.

Just seven years later, chemist Leo Baekeland created the first true synthetic plastic polymer. He was trying to invent an alternative to shellac, a natural, resinous polymer that was used to insulate electrical wires. Shellac was the epitome of a scarce natural material, crucial to industrial enterprise, that was caught in the chokehold of nature's limited capacity to produce. Secreted by a southeast Asian beetle, the resin was painstakingly collected at a rate of one pound over six months. To create his plastic polymer, Baekeland reacted two chemicals, phenol and formaldehyde. The resulting material, which he called "Bakelite," was resistant to heat and electricity, and could be molded, cut or pressed into any shape imaginable. Touted as the "material of a thousand uses," Bakelite was used to make everything from car parts to office equipment to children's toys, and the world was never the same.

According to Robert Malloy, chair of the oldest plastic engineering department in the country, located at the University of Massachusetts at Lowell, the key to a synthetic polymer's limitless potential lies in three main characteristics: the length of its polymer chain, the strength of that chain, and the chemicals that are added during production to give the polymer specific properties. In terms of chain length, Malloy explains, the longer the chain, the tougher, stiffer and more chemically resistant the material it forms tends to be. Chain strength, he says, is determined by the type of chemical bond between the molecules. For a sense of the variation in these bonds, picture the difference between the strength of the plastic seal on a bottle of aspirin, something that is intended to break, with the sheets of plastic laminate made to resist the rounds shot from high-powered rifles.

Chemical additives, Malloy explains, are like secret ingredients that enhance a polymer's function. Some improve processing, ("It could be an oil that makes it flow better during production," Malloy said,) but they're often aimed at boosting aesthetics, such as a dye that masks the product's yellowing due to age, or imparting unique properties, like fire retardants that prevent burning, plasticizers that bestow flexibility, and UV stabilizers that thwart degradation via sunlight exposure.

The beauty of synthetic polymers is that chemists are able to control every aspect of design, arranging these three characteristics in a seemingly infinite number of combinations to produce the desired effect. In 1907, when Baekeland introduced Bakelite to the world of mass-manufacturing, the plastic polymer was superior to its natural counterparts in every way. It could be generated in infinite quantity and tuned to have ideal features, and it possessed a characteristic that nature could never guarantee—flawless consistency.

Bakelite, however, was just the beginning. Over the next thirty years, a flood of plastic-polymer innovation yielded, among others: polyvinyl chloride, a durable, yet versatile building material; nylon, the first synthetic fiber; polyethylene, a tough, but malleable resin used to make blow-molded containers and plastic films; and PET, a glass substitute that, with its resistance to carbon dioxide permeation, remains the standard for carbonated soft drink bottles.

In 1941, V. E. Yarsley and E. G. Couzens, two British applied chemists, in a thin primer entitled "Plastics," declared the material's significance, writing: "Now it can confidently be stated that there is no other material possessing all these qualities as does the average plastic." It was better than wood, which was prone to rot and unpredictable with its uneven grain; porcelain, which was heavy and broke easily; metal, which rusted, weighed a ton, and was difficult to manipulate; and marble, which, again, was heavy, as well as rare and, therefore, expensive.

When Yarsley and Couzens wrote, plastics were still in their infancy. Plastic production didn't really hit its stride until World War II, when the military enlisted it to make helmets, mortar fuses, canteens, and plane parts, and yearly production in the U.S. nearly tripled. Post-war, with all of that manufacturing infrastructure in place, production would kick into overdrive, but with a new goal—the production of consumer goods. Yet the authors, in their enthusiasm, ventured a prophesy in which they imagined the life of a future "dweller in the 'Plastic Age' that is already upon us," writing:

> "This 'Plastic Man' will come into a world of colour and bright shining surfaces, where childish hands find nothing to break, no sharp edges or corners to cut or graze, no crevices to harbour dirt or germs...he is surrounded on every side by this tough, safe, clean material which human thought has created...As he grows up he cleans his teeth and brushes his hair with plastic brushes with plastic bristles, clothes himself in plastic clothes of synthetic silk and wool...writes his lessons with a plastic pen and does his lessons with books bound in plastic...The windows of [his] school...are unbreakable, and transmit the life-giving ultra-violet rays, and the frames...are of moulded plastic, light and easy to open, and never requiring any paint to prevent them from warping or rusting...but lest this picture seem too coldly hygienic, remember that everywhere there is a riot of colour and every kind of surface from dull matt to a mirror-finish that circumstances demand."

The prophesy follows the 'Plastic Man' throughout the course of his life, during which he lives and works in a "universal plastic environment," and turns to plastic for beauty and leisure. At the end of his life, we find the 'Plastic Man' "getting tired and old." The authors continue:

> "His own teeth are gone and he wears a plastic denture with 'silent' plastic teeth and spectacles of plastic with plastic lenses...until at last he sinks into his grave hygienically enclosed in a plastic coffin."

If the modern reader perceives Yarsley and Couzens' dream, featuring plastic's near complete integration into our lives, as ironic, it's only because it so closely mirrors present reality. To this day, plastic continues to make good on its promise as a "miracle material." Even its harshest critics won't begrudge a soldier his body armor or a doctor her sterilized equipment. There is, arguably, not a single industry—transportation, technology, clothing, food, medical, aerospace—that plastics hasn't transformed in its short existence.

Yet, in the same short time, plastic trash has come to live as more of a scourge in the public perception than any other material waste. Unlike discarded paper, wood or metal scrap, plastic trash evokes responses of revulsion that have begun to carry over, condemning plastics in general. Where then did the "miracle material" go wrong?

The tragic despoilment of the ocean that now exists, with plastic floating and littering remote corners of the world, is, in fact, not about plastic as much as it is about us. For all that plastics have contributed to society, the material should be celebrated. But Yarsley and Couzens' dream wasn't realized in quite the way they had imagined. What they didn't anticipate is that we would take all of that great plastic stuff and throw it out. If there's blame for plastic's emerging role as environmental blight and contaminant, it belongs with us for the way we've chosen to use it.

First, we employ plastics to make things that we use once and then throw away forever. It's easy to think of plastic as being synonymous with disposability for the near monopoly it holds on packaging. But our transition from a culture of thrift to one that embraces disposability pre-dated plastics by at least half a century. Where people used to buy their goods, like food and cleaning supplies, out of bulk barrels, by 1900, companies, like Procter & Gamble and Heinz, had started selling products in individually wrapped "throwaway" packages, advertised as convenient or sanitary. Glass bottles were used, but cardboard and paper accounted for the greatest quantity of packaging material—a result of their cheapness and abundance after we learned to make them from wood pulp as opposed to cloth scraps. In 1905, one Massachusetts company promoted their individually boxed toothbrushes as reaching the customer clean and sterilized, with the warning, "Do not buy from a fingered pile of dusty, germ-laden tooth brushes, handled by nobody knows who." The Industrial Revolution also drove the adoption of a disposable culture, as machines now mass-produced goods that were once painstakingly handmade or made at home. In the first twenty-five years of the 20th century, the sheer volume of products manufactured in America increased almost threefold.

So when plastic was co-opted for packaging in the 1950s, it wasn't that packaging was new, it was that plastic was so much better at it than any other material. Polyethylene, strong, flexible and cheap, was tapped as the poster polymer for packaging and is considered the first "mass plastic." While Bakelite had built its reputation on durability, polyethylene became associated with disposability. The polyethylene squeeze bottle entered the market in 1947 as a deodorant container. Three years later, squeeze bottles were being pumped out at a rate of a hundred thousand per day, and by 1958, polyethylene was the most produced plastic, used to package everything from shampoo to milk. One of its greatest benefits is its ability to prolong the shelf-life of food, while, at the same time, allow customers to see the package's contents. Also, as plastic weighs so much less than glass or metal, its use in packaging saves significantly on energy expended both during the production and transportation of goods.

But there has been a price to pay for making plastic the quintessential disposable material. It doesn't biodegrade and is notoriously difficult to recycle. Today, disposable plastic packaging accounts for the most significant use of plastics. More than a third of the plastic produced worldwide each year, (two hundred and sixty million tons as of 2008), is destined to become trash within the same year.

Our second misstep with plastics is that we've allowed them to be artificially cheap. At the beginning of the 20th century, the petroleum industry ramped up significantly, as greater quantities of crude oil were extracted for transportation fuels. But it was also discovered that crude oil was ideal for making plastic, and it quickly replaced wood and cotton as the primary plastic feedstock. To this day, plastic production economically piggybacks on transportation fuels, with a small percentage of every barrel of oil extracted going toward plastic production—about four per cent for raw material and another four per cent as the energy to drive manufacturing. In this way, the price of plastics doesn't bear the true cost of obtaining the material, which allows us to severely undervalue plastic. As a result, we make more plastic products than we would otherwise and perceive them as that much more disposable. It is worth considering how expensive plastics might be if the cost of all oil extraction infrastructure— platforms, refineries, and tankers—were borne by plastic alone.

With the realization that petroleum is a limited resource, the search is on to find viable alternative feedstocks. The products made from some of these feedstocks, which are mainly crops, including corn, potato starch, sugar cane, vegetable oils, and switchgrass, are designed to biodegrade unlike petro-based plastics. But, while these bioplastics sound promising, they have drawbacks. After more than a decade of effort, bioplastics are still at least twice as expensive as conventional plastics and inferior in terms of quality. Scaling up has presented a challenge, with bioplastics currently capturing less than 0.2 per cent of total plastic production worldwide. Also, bioplastics can't be recycled in traditional recycling plants. A bottle made of poly-lactic acid, a corn-based polymer, looks identical to one made from a petro-based polymer. But during recycling, the corn bottle will not only melt first at a lower temperature than the standard bottle, but it becomes intensely sticky, and can halt the entire recycling process, sabotaging the plant's machinery. This has doomed bioplastics to the landfill.

The other big criticism plaguing bioplastics is that many of its feedstocks are also food crops, in effect, pitting one man's goods against another man's meal. But the question here is: even if a non-food crop like switchgrass were to become a viable plastic feedstock, would we really want to be clearing new land for the purpose of making new plastic?

But perhaps our greatest transgression with plastic amounts to our failure to design either its polymers or products with their fate in mind. In a way, it makes sense that the chemists who invented plastics would neglect to consider what happened to the material once it was discarded. After all, they lived in a world where things either biodegraded or were easily recycled. But in plastic, we created a material that defeats nature's process of decay, and as of today, we still have no comprehensive sustainable solution to get rid of or reuse it.

Recycling plastics could be easy. But of the seven major types of plastic we use today, only one of them—PET, which is used to make beverage bottles—can be recycled to any great effect. The main reason for this, is chemical additives. When it comes to recycling, the ability to purify is key. Melting plastics, however, doesn't purify them. The only hope recycling engineers have is to know what additives are in the plastic they're working with, so they can apply specific removal methods. But additive use in plastics is considered proprietary. This means that each company that develops polyethylene, for example, can have its own recipe, which can include several chemicals to enhance its particular brand of polyethylene. The company then, however, has no obligation to reveal that recipe, leaving a would-be recycling engineer completely in the dark as to what chemicals he's working with and what products the recycled material could potentially be used to make. For instance, some additives are toxic and would contaminate a stream of recycled material intended for food-grade containers in its next life. (PET is so easily recycled because a consortium of PET producers have set global standards, allowing only certain additives to be used, so recycling engineers know where they stand. This cooperation has yet to spread to manufacturers of other plastic types.)

The other main obstacle to recycling is that products still aren't designed for it. The ease with which two products can be separated is crucial to the recycling process. Just choosing to use a snap fit to combine two pieces as opposed to fusing them together with an adhesive can make a world of difference to a product's recycling eligibility.

Furthermore, because plastic is artificially cheap, it has cost less to make virgin plastic than to use recycled plastic. Manufacturers, therein, have had no incentive to retrieve their materials or invest in the improvement of recycling technology. As a result, the responsibility to provide recycling plants has fallen to municipalities that can afford to build and maintain them. This immediately excludes many towns in developing countries and, as there is no profit in it, recycling in industrial countries remains anemic. In 2008, the U.S. recycled just under seven per cent of the plastic it generated—a number that might actually decrease due to the recent spate of state budget cuts. Money for recycling has been reduced or cut, causing recycling plants in several states, including California and Massachusetts, to close.

Still, there is a growing belief that recycling is the only solution to the environmental challenges plastic waste presents. The ultimate goal, termed "closed loop" or "zero waste," is to turn recycled plastic into a feedstock for itself. Over the last decade, according to Ed Koisor, a polymer chemist and plastics recycling expert based in London, a slow but steady movement to develop polymers using less toxic additives and design products for disassembly has begun to take shape.

In June of 2008, Koisor helped to open the first food-grade plastics recycling plant in the U.K. While at this point, the plant can only recycle clear and light blue bottles made of PET and high-density polyethylene, or HDPE, it is able to turn the plastic into raw material for food-grade plastic packaging. The plant, funded by government grants and private investment, employs a new technology that sorts the plastic and uses the combination of a powerful magnet, electric current, caustic wash, heat, and vacuum pressure to remove contaminants. The PET, says Koisor can be recycled many times, while the HDPE can endure about five cycles before it needs a boost from a strengthening chemical called a protectorant.

Conventional recycling plants are only able to turn PET and polyethylene into polyester fiber for fleece jackets or playground equipment, respectively. As these products can't be made into new products, the process is called "downcycling." So the U.K. plant, with its food packaging-to-food packaging cycle marks a genuine step toward "zero waste." Diverting an estimated thirty-five thousand tons of bottles from the landfill each year, the plant is able to sell its recycled raw material for a price equivalent to that of virgin plastic.

"Is it more expensive to make a product using recycled materials? No," Koisor said. "Maybe ten years ago, but thanks to improvements in sorting processes, the price is at parity." Also, he adds, because the price of oil has gone up, so has the price of virgin plastic material, helping to level the playing field. The philosophy behind the plant, Koisor explains, "is that if recycled material is equivalent and can displace virgin material from the new product, then it should be valued at the same price." That leaves the company with a choice between virgin and recycled—a choice that will be made and is increasingly being made, Koisor said, by the demands for a greener product from educated consumers.

But should the price of recycled raw plastic material stop at parity with virgin material, leaving the tie to be broken by vociferous customers? Shouldn't the goal be to eliminate the choice and make it cheaper? Because only when a container of recycled plastic material costs less than a container of virgin plastic material will manufacturers have a true incentive to factor in the end-of-life scenario for the products they design.

Demand for plastic is growing worldwide. The populations of developing countries, as they aspire to a higher quality of life, are increasingly adopting plastics for their superior performance and affordability in place of traditional materials like wood, metal, glass and paper. Where in 1950, annual global plastic production was a half million tons, by 2008, it skyrocketed to two hundred and sixty million tons, and continues to grow by nine per cent each year. That means that within the first ten years of this century, nearly as much plastic will be produced as during the entire last century.

To have created this versatile material, enlisted it for such ephemeral use, and not planned for its obsolescence is to have abandoned plastic only halfway to becoming what we want and need it to be. As a result, sixty years later, it is floating in every ocean on the planet. The danger now is if we choose not to realize plastic's full potential as a material that can be used in a virtuous cycle, but rather focus on developing the next miracle material that is perhaps cheaper and more versatile with no thought to its end. To make this choice is to take a great risk and should give us pause to imagine what might be filling our oceans and washing up on shores sixty years from now.

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Kara Lavender Law, Ph.D.; physical oceanographer at SEA; Woods Hole, MA
Giora Proskurowski, Ph.D.; chemical oceanographer at SEA; Woods Hole, MA
Miriam Goldstein; Ph.D. candidate in biological oceanography at SCRIPPS; San Diego, CA
Noni & Ron Sanford; residents; Big Island, HI
Megan Lamson; Hawaii Wildlife Fund debris project coordinator; Big Island, HI
Nikolai Maximenko, Ph.D.; physical oceanographer at Univ. of Hawaii; Honolulu, HI
Andrew Titmus; seabird researcher; Hawaii Pacific Univ.; Waimanalo, HI
Carey Morishige; outreach coordinator, NOAA Marine Debris Program; Honolulu, HI
James Callahan; ocean advocate and sailor, Honolulu, HI
Marieta Francis; exec. director; Algalita Marine Research Foundation; Long Beach, CA
Charles Moore; captain and founder of Algalita; Long Beach, CA
Suzanne Frazer; ocean advocate and founder of B.E.A.C.H.; Honolulu, HI
Dean Otsuki; ocean advocate and founder of B.E.A.C.H.; Honolulu, HI
Phillip Gschwend, Ph.D.; civil engineer and organic chemist at MIT, Cambridge, MA
Robert Malloy, Ph.D.; polymer chemist and chair of Plastics Engineering Dept. at UMass, Lowell; Lowell, MA

### II. Phone interviews

*Peter Niiler, Ph.D.; physical oceanographer at SCRIPPS
*Hideshige Takada, Ph.D.; geochemist at Tokyo University of Agriculture and Technology
Richard Thompson, Ph.D.; marine scientist at the University of Plymouth, U.K.
Michael Moore, Ph.D.; biologist at WHOI
*Susie Holst; NOAA diver
Doug Woodring; ocean advocate and founder of Project Kaisei
Beth Terry; plastic acetic, blogger
Ed Koisor, Ph.D.; polymer chemist, sustainable plastics consultant, recycling expert
Marc Ward; sea turtle advocate, based in Punta Pargos, Costa Rica
Michael Dworsky; head of solid waste division on the Big Island of Hawaii
*Marcus Eriksen, Ph.D.; outreach; Algalita Marine Research Foundation
Anna Cummins; outreach; Algalita Marine Research Foundation
*Tim Veenstra; pilot and head of NOAA's High Seas Ghostnet Project

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Bill Gilmartin, Ph.D; biologist and founder and president of Hawaii Wildlife Fund
Ian McCable; J.D. candidate in Maritime Law at the University of Oregon
Kris McElwee; outreach coordinator, NOAA Marine Debris Program
*Sarah Klain; sea turtle conservationist with Peace Corps in Micronesia
*Jack Frazier, Ph.D.; sea turtle biologist; Smithsonian Institution
*Colette Wabnitz; Ph.D. candidate at the University of British Columbia

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**VII. Events Attended**

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