PLASTIC PLANET

These chains of molecules have transformed society during the past century, for better and for worse

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THERE WAS A TIME when the human habitat wasn't saturated with plastics. Somehow, people managed with other materials.

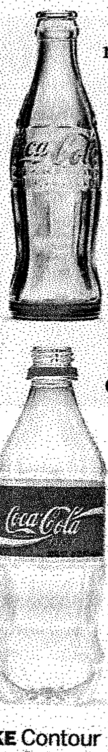
The Coca-Cola bottle, the most common of objects that existed before and after plastics, illustrates how different life used to be.

Coke introduced the glass contour, or "hobble skirt," bottle in 1915. The iconic green bottle changed little through the Stock Market Crash of 1929, the Berlin Airlift, and Elvis' first appearance on "The Ed Sullivan Show."

Then the plastic version of the contour appeared in 1993. It has similarities to its predecessor. It bears the same logo. It is blow-molded into more or less the same shape. And aside from another wonder of chemistry, the high-fructose corn syrup in the modern formula of Coke, it holds the same stuff.

The resemblance ends there. If a glass bottle drops on the floor, it will shatter. Today's Coca-Cola plastic bottles, made with polyethylene terephthalate (PET), will just bounce. Glass bottles were heavy, each weighing nearly 1 lb. The plastic versions weigh about an ounce. And today's standard plastic Coke bottles hold 20 oz, more than three times what the typical glass bottles contained.

Over the past century, nearly every object we touch throughout the day has undergone at least as many changes as that Coke bottle has, thanks to plastics. Our everyday objects are lighter, more durable, cheaper to manufacture, sleeker, and more sanitary than their predecessors. The world before plastics was that of butcher paper, tin soldiers, wooden crates, broken glass, and rusting metal—less convenient and less abundant in consumer goods than today.



COCA-COLA

COKE Contour Coca-Cola bottles in glass (1915) and in plastic (1993).

But it was also a world of less trash bobbing in the sea.

When the first issue of *Industrial & Engineering Chemistry News Edition*, which later became C&EN, arrived on rolltop desks in 1923, it reached many of the chemists who were changing that old world. The 1920s ushered in the Golden Age of Plastics.

That isn't to say plastics didn't exist in 1923. They did, and the public was long familiar with them. But the choice of quality materials was limited.

Celluloid had been around since 1868. That year, John Wesley Hyatt, endeavoring to win a $10,000 prize offered by billiard ball manufacturers for a practical substitute for ivory, concocted a mixture of nitrocellulose and camphor that would be the dominant plastic for the next half-century. As C&EN's "News Scripts" remarked 100 years later, celluloid would become the stuff of "piano keys, celluloid collars, dice, combs, and numerous fires."

The first commercial, fully synthetic plastic was the thermoset Bakelite, invented by Leo H. Baekeland. Independently wealthy from his development of specialized photographic paper, the Belgian-born Ph.D. chemist erected a laboratory on his Yonkers, N.Y., estate. There he experimented with phenol and formaldehyde in the hopes of making better lacquers and varnishes. When his experiments yielded a hard material in 1907, Baekeland realized he had stumbled across something even better.

In 1910, General Bakelite Co. began filling orders for the phenolic resins out of its plant

American Chemistry Council, resin production reached 14.6 million tons. In 2012, it hit 53.0 million tons.

But how much is too much? As plastics became ubiquitous, they brought dire consequences. Plastic film presented the first, and gravest, problem. Consumers were reusing dry-cleaning bags and other polyethylene films as pillowcases and for other purposes they weren't designed for. As a result, 20 children suffocated on thin plastic films during the first three months of 1959 alone. In response, the industry launched a public awareness campaign to warn parents of the danger, and plastic processors made thicker, less hazardous films.

In 1974, B.F. Goodrich disclosed that three of its workers at its Louisville PVC plant died from a rare form of liver cancer, angiosarcoma, which normally killed only 21 people per year throughout the entire U.S. The episode prompted new regulations meant to limit workers' exposure to the PVC raw material vinyl chloride.

IN THE 1990s AND 2000s, researchers fingered phthalate ester plasticizers, used to soften PVC, as agents of endocrine disruption and other adverse health effects. Bisphenol A, used to make polycarbonate, also came under fire as an endocrine disrupter. Leading retailers such as Walmart and Toys 'R Us banished polycarbonate baby bottles from their shelves.

Litter might be the most pervasive problem of plastics consumption. The problem is more serious than the eyesore of plastic bags entangling trees. Plastics may be choking our oceans. Over the past decade, research has intensified into gyres, vast regions of the world's oceans where currents and winds trap massive amounts of plastic debris. Scientists are only beginning to sort through the ecological effects of all this garbage.

Are plastics worth the trouble? If all plastics did was facilitate consumerism, perhaps not. But we don't just want plastics, we need them.

Medicine provides the most striking example. What patient wants a glass intravenous drip bouncing over her head in a speeding ambulance? Plastics in the form of disposable syringes, catheters, and polyethylene hip replacement joints have also become indispensable tools of the medical trade.

Besides, synthetic polymers have their own environmental advantages. For example, plastics have made cars lighter and more fuel efficient. In 1960, the average American car contained less than 20 lb of plastics and composites. Today, cars hold about 380 lb, according to ACC. The average fuel economy for the 2011 model year was 22.8 mpg. Had it not been for plastics, ACC claims, those same vehicles would have gotten only 16.2 mpg.

A growing movement in the plastics industry seeks to resolve the conflict between our need for plastics with the environmental consequences of using them. The initiative has big backers, including giants such as Coca-Cola and H. J. Heinz, which are using PET resins made with ethylene glycol derived from sugarcane.

Smaller, younger firms, point to a potential new era for the plastics industry ahead and a new, more sustainable world for the rest of us. Some of them presented at the BioPlastek Forum, held earlier this summer in San Francisco. It is one of the few plastics conferences, if not the only one, where presentation slides show oil spills and oil sands mining to demonstrate some of the uglier consequences of petroleum-based plastics.

Ryan Williams, who holds the title "Good Cop" at Method Products, talked about the first bottle made from ocean plastic. The company found a beach on the far reaches of Hawaii where plastic trash from the North Pacific Gyre piles up to 4 feet high in some places. Method collected several tons of that plastic, heavily oxidized from years of exposure, and shipped it to California, where it was blended with recycled polyethylene and molded into hand soap bottles.

Williams told the audience that only 10% of the 300 million tons of plastic made worldwide per year is recycled. "That totally sucks, right?" he asked. "That's why that plastic that I pick up on the beach in Hawaii is actually the most sustainable source of plastic in the world." ■

From C&EN Archives

In the 1950s, the field of polymers was where chemists and chemical companies were having the most impact on the lives of ordinary Americans, and C&EN chronicled it.

The Plastic Film Menace The American public learned in the late 1950s that plastics could be dangerous as well as helpful. On June 8, 1959, C&EN reported that 20 children—mostly infants—were smothered to death by polyethylene film during the first three months of 1959 alone. Unaware of the dangers of the new materials, adults were reusing dry-cleaning bags as mattress covers and pillowcases. Congress later passed a law requiring warning labels on plastic film. These labels are still in use today. Manufacturers also made films thicker and launched a public awareness campaign.

Plastic Popcorn C&EN nailed the simile when it explained expandable polystyrene (EPS) to readers on March 15, 1954. "Material comes in tiny hard beads impregnated with an undisclosed foaming agent that reacts on heating somewhat like the moisture within a kernel of popcorn," the article stated when describing materials being developed by Koppers Industries. The author presciently noted that the material had better insulating properties than cork, glass fiber, and mineral wool. Insulation, whether in an attic or a coffee cup, is the dominant use of EPS today. However, EPS and polystyrene foam would become emblematic of the plastic waste problem by 1990, forcing McDonald's to drop polystyrene foam from its packaging.

Instead of continuing with polyesters, the pair of chemists turned their attention to the promising products of the condensation of dibasic acids and diamines. Efforts coalesced around the polyamide made from adipic acid and hexamethylenediamine. That new polymer, nylon 6,6, would cause a public sensation like no polymer had done before or has since. Some 800,000 pairs of nylon stockings were sold on May 15, 1940, the day of their introduction.

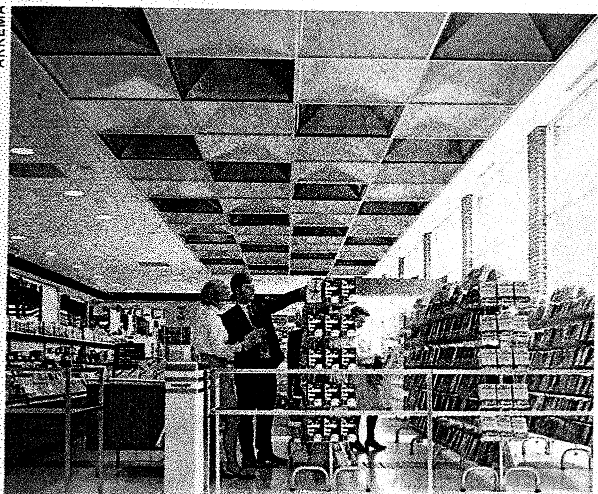
Carothers' influence stretched beyond DuPont. For example, John R. Whinfield of Calico Printers' Association would pick up the polyester work that Carothers set aside. By reacting terephthalic acid with ethylene glycol, he made PET, the polyester of the Coke bottle and the leisure suit.

AP/TUPPERWARE

SOFT SELL By the late 1950s, Tupperware found that gatherings of potential customers, hosted by independent saleswomen, were the best means to sell its polyethylene housewares.

Plastics were enlisted in the war effort. Among the materials the Allies depended on during World War II were polyethylene insulation for radar cable, Plexiglas fashioned into bomber noses, and nylon parachute fabric.

ARKEMA



GROOVY Plexiglas was a common decorative element in the 1960s and 1970s.

After the war, the plastics industry retooled to meet peacetime demand. The period celebrated the marriage, still strong to this day, of the chemical and oil industries. This union allowed the plastics industry to achieve economies of scale far beyond what would have been possible by extracting raw materials from coal.

Writing in C&EN in 1954, DuPont chemist E. F. Izard praised PET as the ideal polymer to commercialize because it is derived from readily available ethylene glycol and *p*-xylene. "However, this situation developed only in the postwar period when *p*-xylene became available from the oil companies as a result of their hydroforming processes," he remarked.

By the 1950s, polymer chemistry had matured into a sophisticated applied science, says Jeffery L. Meikle, professor of American studies and art history at the University of Texas, Austin, and author of "American Plastic: A Cultural History." "The phrase that I found over and over again was 'tailor-made,' meaning that the chemist knew what he wanted and he could specify it," he says. "As opposed to 'Here's some gunk. What can we do with it?' "

What the polymer chemists of this era wanted most was an alternative to ICI's high-pressure polyethylene process, which yields low-density polyethylene. Scientists at DuPont, Phillips Petroleum, and other firms, as well as future Nobel Laureate Karl Ziegler of the Max Planck Institute for Coal Research, were commercializing new catalysts and processes by the mid-1950s. But the material from low-pressure processes wasn't a substitute for ICI's low-density product. High-density polyethylene would be a new plastic, stiffer than the existing polyethylene and suited to new applications such as today's milk jugs and shopping bags.

Polypropylene grew out of such efforts, too. Though they wouldn't receive credit for 30 years, Phillips chemists J. Paul Hogan and Robert L. Banks discovered polypropylene in 1951.

Engineering polymers—developed for the purpose of replacing metals—made up the last major class of materials to spring from the Golden Age of Plastics. In 1957, C&EN heralded General Electric's Lexan polycarbonate, "not yet out of the laboratory," as "strong as steel." The same company unveiled polyphenylene oxide in 1964, touting its great chemical resistance. DuPont made a stable polymer out of polyacetal, originally discovered by Staudinger, and launched it as Delrin in 1960. "DuPont believes that Delrin is the first plastic with strength properties that approach those of metals," C&EN reported in 1959.

Inspired by the new materials, entrepreneurs and designers increasingly asked, "Can we make it out of plastic?" One application after another took hold. A picture in C&EN from 1955 shows a Dow scientist dropping polyethylene bags filled with sand from "three times the height a housewife would lift them normally," to demonstrate that the bags were more than adequate for real-world use. Jon M. Huntsman Sr., founder of Huntsman Corp., got his start in plastics by pioneering the use of polystyrene foam to make egg cartons. In 1970, Pepsi would launch the 2-L PET soda bottle, designed by Nathaniel Wyeth of DuPont.

PLASTICS WENT HAND in hand with postwar prosperity, Meikle says. The availability of cheap plastic goods helped working Americans attain a middle-class lifestyle. "The ease of making those things might have contributed to the explosion of consumer products after World War II and to the sense ordinary folks had of being able to have more things than they could ever have before," he says.

The plastics business exploded. U.S. production of plastic resins was 1.2 million tons in 1951, according to the U.S. Tariff Commission. By 1973, according to the in Perth Amboy, N.J. Before long, Bakelite was being molded into telephones, pot handles, and art deco radio enclosures. By 1924, Baekeland had grown so respected among chemists that he would become president of the American Chemical Society.

More than a few chemists followed Baekeland's example and got to work synthesizing new polymers. At the time, most scientists thought polymers were a kind of colloidal aggregate, held together by "partial valencies." Molecular weights greater than 5,000, they thought, couldn't exist.

Hermann Staudinger, professor of organic chemistry at the Swiss Federal Institute of Technology, had a different idea.

He postulated in 1920 that polymers were long-chain "macromolecules" strung together by strong covalent bonds. He received the Nobel Prize for his work in 1953.

Staudinger's generation of polymer chemists of the 1920s and 1930s would be history's most prolific inventors of synthetic materials. "You might say that the industry took off after World War I," says Robert J. Bauman, an industry veteran and president of Polymer Consulting International. A period of peace brought an unprecedented opportunity for American chemists to collaborate with European colleagues. "So from 1918 to 1940, most of the basic materials were invented," he says.

DURING THIS TIME, Otto Röhm, of Germany's Rohm and Haas, would develop polymethyl methacrylate, marketed by the company's U.S. affiliate as Plexiglas. Chemists at the German chemical cartel I.G. Farben would make polystyrene, discovered in the 19th century, a useful plastic. Similarly, Waldo L. Semon of B.F. Goodrich would tame brittle polyvinyl chloride with plasticizers.

After pressurizing ethylene in a vessel at a British Imperial Chemical Industries (ICI) laboratory in 1933, Reginald Gibson and Eric Fawcett found a waxy residue, which would later be known as polyethylene, the plastic produced in the biggest volume today. Polytetrafluoroethylene, known as Teflon, was also a serendipitous discovery, made by DuPont's Roy J. Plunkett while he was working with refrigerants.

DuPont was the wheelhouse of polymer chemistry during the period between World Wars I and II. In 1928, the company hired Wallace H. Carothers, a Staudinger devotee, away from Harvard University to work on polymers at DuPont's Experimental Station in Wilmington, Del. DuPont promised him a $6,000 annual salary and the chance of doing well-funded basic research. Carothers' time at DuPont, which ended sadly when he deliberately bit down on a cyanide capsule to end his own life in 1937, would be consequential for polymer chemistry.

Carothers wanted to build polymers that pushed past the old theoretical limits and thus prove Staudinger right. He and research partner Julian Hill worked on condensation polymers of dibasic acids and diols. A "cold drawing" procedure they devised to align the polyester chains down the length of a fiber interested DuPont brass, who coveted a synthetic replacement for Japanese silk.