The Brilliant Inventor Who Made Two of History's Biggest Mistakes

A century ago, Thomas Midgley Jr. was responsible for two phenomenally destructive innovations. What can we learn from them today?

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Published March 15, 2023 Updated March 17, 2023

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It was said that Thomas Midgley Jr. had the finest lawn in America. Golf-club chairmen from across the Midwest would visit his estate on the outskirts of Columbus, Ohio, purely to admire the grounds; the Scott Seed Company eventually put an image of Midgley's lawn on its letterhead. Midgley cultivated his acres of grass with the same compulsive innovation that characterized his entire career. He installed a wind gauge on the roof that would sound an alarm in his bedroom, alerting him whenever the lawn risked being desiccated by a breeze. Fifty years before the arrival of smart-home devices, Midgley wired up the rotary telephone in his bedroom so that a few spins of the dial would operate the sprinklers.

In the fall of 1940, at age 51, Midgley contracted polio, and the dashing, charismatic inventor soon found himself in a wheelchair, paralyzed from the waist down. At first he took on his disability with the same ingenuity that he applied to maintaining his legendary lawn, analyzing the problem and devising a novel solution to it — in this case, a mechanized harness with pulleys attached to his bed, allowing him to clamber into his wheelchair each morning without assistance. At the time, the contraption seemed emblematic of everything Midgley had stood for in his career as an inventor: determined, innovative thinking that took on a seemingly intractable challenge and somehow found a way around it.

Or at least it seemed like that until the morning of Nov. 2, 1944, when Midgley was found dead in his bedroom. The public was told he had been accidentally strangled to death by his own invention. Privately, his death was ruled a suicide. Either way, the machine he designed had become the instrument of his death.

Midgley was laid to rest as a brilliant American maverick of the first order. Newspapers ran eulogies recounting the heroic inventions he brought into the world, breakthroughs that advanced two of the most important technological revolutions of the age: automobiles and refrigeration. "The world has lost a truly great citizen in Mr. Midgley's death," Orville Wright declared. "I have been proud to call him friend." But the dark story line of Midgley's demise — the inventor killed by his own invention! — would take an even darker turn in the decades that followed. While The Times praised him as "one of the nation's outstanding chemists" in its obituary, today Midgley is best known for the terrible consequences of that chemistry, thanks to the stretch of his career from 1922 to 1928, during which he managed to invent leaded gasoline and also develop the first commercial use of the chlorofluorocarbons that would create a hole in the ozone layer.

Each of these innovations offered a brilliant solution to an urgent technological problem of the era: making automobiles more efficient, producing a safer refrigerant. But each turned out to have deadly secondary effects on a global scale. Indeed, there may be no other single person in history who did as much damage to human health and the planet, all with the best of intentions as an inventor.

What should we make of the disquieting career of Thomas Midgley Jr.? There are material reasons for revisiting his story now, beyond the one accidental rhyme of history: the centennial of leaded gasoline's first appearance on the market in 1923. That might seem like the distant past, but the truth is we are still living with the consequences of Midgley's innovations. This year, the United Nations released an encouraging study reporting that the ozone layer was indeed on track to fully recover from the damage caused by Midgley's chlorofluorocarbons — but not for another 40 years.

The arc of Midgley's life points to a debate that has intensified in recent years, which can be boiled down to this: As we make decisions today, how much should we worry about consequences that might take decades or centuries to emerge? Will seemingly harmless G.M.O.s (genetically modified organisms) bring about secondary effects that become visible only to future generations? Will early research into nanoscale materials ultimately allow terrorists to unleash killer nanobots in urban centers?

Midgley's innovations — particularly the chlorofluorocarbons — seemed like brilliant ideas at the time, but 50 years taught us otherwise. Pondering Midgley and his legacy forces us to wrestle with the core questions at the heart of 'longtermism,' as the debate over long-term thinking has come to be called: What is the right time horizon for anticipating potential threats? Does focusing on speculative futures distract us from the undeniable needs of the present moment? And Midgley's story poses a crucial question for a culture, like ours, dominated by market-driven invention: How do we best bring new things into the world when we recognize, by definition, that their long-term consequences are unknowable?

Invention was in Midgley's blood. His father was a lifelong tinkerer who made meaningful contributions to the early design of automobile tires. In the 1860s, his maternal grandfather, James Emerson, patented a number of improvements to circular saws and other tools. As a teenager growing up in Columbus, Midgley showed early promise in deploying novel chemical compounds for practical ends, using an extract from the bark of an elm tree as a substitute for human saliva while throwing spitballs on the baseball field. A high school chemistry class inaugurated what would prove to be a lifelong obsession with the periodic table, which then was rapidly being expanded thanks to early-20th-century discoveries in physics and chemistry. For most of his professional career, he carried a copy of the table in his pocket. The spatial arrangement of the elements on the page would help inspire his two most significant ideas.

After graduating from Cornell in 1911 with a degree in mechanical engineering, Midgley moved to Dayton, Ohio — arguably the leading innovation hub in the country at the time. History generally remembers Dayton for the Wright brothers, who sketched out their plans for the Kitty Hawk flight there, but the original attraction that drew inventors to the city was an unlikely one: the cash register, which for the first time enabled store owners to automate the record of transactions — and prevent employee theft. By the time Midgley joined the National Cash Register company in 1911, it had become a powerhouse, selling hundreds of thousands of machines around the world. It was there that Midgley first began hearing stories about Charles Kettering, who devised NCR's mechanized system for clerks to run credit checks on customers directly from the sales floor, along with the first cash register to run on electric power.

Firms like NCR had begun experimenting with a new organizational unit, the research lab, in the spirit of the polymathic "muckers" whom Thomas Edison had assembled at his plant in Menlo Park, N.J. A few years after joining NCR, Kettering turned his attention to the emerging technology of the automobile, forming his own independent research lab known as Delco, short for Dayton Engineering Laboratories Company, in 1909. There he concocted a device that proved crucial in transforming automobiles from a hobbyist's pursuit to a mainstream technology: the electric ignition system. (Before Kettering's breakthrough, automobiles had to be started with an unwieldy — and sometimes dangerous — hand crank, which required significant physical force to operate.) By 1916, Delco had been acquired by the corporation that would become General Motors, where Kettering would go on to work for the rest of his career.

Shortly after the acquisition, Midgley applied for a job in Kettering's lab and was hired immediately. He was 27; Kettering was 40. After finishing a minor project that commenced before his arrival, Midgley walked into Kettering's office one day and asked, "What do you want me to do next, Boss?" Kettering wrote after Midgley's death. "That simple question and the answer to it turned out to be the beginning of a great adventure in the life of a most versatile man."

The technical riddle Kettering tasked Midgley with solving was one of the few remaining impasses keeping the automobile from mass adoption: engine knock.

As the name implies, for the automobile passenger, engine knock was not just a sound but a bodily sensation. "Driving up a hill made valves rattle, cylinder heads knock, the gearbox vibrate and the engine suddenly lose power," Sharon Bertsch McGrayne writes in her excellent history of modern chemistry, "Prometheans in the Lab." The problem was made all the more mysterious by the fact that no one had any idea what was causing it. ("We don't even know what makes an automobile run," Kettering admitted at one point.) In a sense, the question that Kettering and Midgley set out to solve was figuring out whether knock was an inevitable secondary effect of a gas-powered engine, or whether it could be engineered out of the system.

To investigate the phenomenon, Midgley devised a miniature camera, optimized for high-speed images. The footage he eventually shot revealed that fuel inside the cylinders was igniting too abruptly, creating a surge of pressure. The unpleasant vibrations passengers were feeling reflected the fundamental fact that energy was being wasted: rattling the bones of the car's occupants instead of driving the pistons.

Starting in 1923, leaded gasoline — marketed under the brand name Ethyl — helped eliminate engine knock, fueling the rise of 20th-century car culture and exposing billions of people worldwide to dangerous levels of lead. Wisconsin Historical Society, via Getty Images

The footage at least gave the problem some specificity: How do you make the fuel combust more efficiently? In the early days, Midgley was groping in the dark; his training was as a mechanical engineer, after all, not as a chemist. One of his first lines of inquiry came from a bizarre suggestion from Kettering — that perhaps the color red could somehow improve the fuel's combustion. Kettering had long been impressed by the way that leaves of the trailing arbutus plant could turn red even when covered by a layer of snow, somehow capturing the energy of the sun's rays more effectively than other plants. Perhaps adding a red dye to the fuel would solve the problem of knock, Kettering suggested. So Midgley used iodine to dye the fuel red, and it did seem to have some mild antiknock properties. Ultimately he realized that it was the iodine itself, not its color, that was the active agent in subduing the knock. It wasn't a solution per se, but it suggested something important nonetheless: that the ultimate solution would come from chemistry, not from engineering.

The search for that solution would ultimately last five years. Kettering later said that Midgley and his team tested 33,000 different compounds. For most of that period, they meandered in a random walk through the periodic table, adding elements to the fuel to see if they did anything to mitigate engine knock. "Most of them had no more effect than spitting in the Great Lakes," Midgley recalled years later.

The first material advance came via a newspaper article that Kettering stumbled across, reporting the discovery of a new "universal solvent" in the form of the compound selenium oxychloride. When added to the fuel, the compound produced mixed results: Knock was reduced considerably, but the new fuel eroded spark plugs almost on contact. Midgley kept searching, systematically plowing through a new version of the periodic table that had recently been introduced, identifying promising clusters of elements, effectively teaching himself industrial chemistry on the fly. He soon discovered that the further you moved toward the heavy metals clustered together on the table, the more the engine knock dissipated. Soon the random walk through the elements became a beeline to what was, at the time, the heaviest metal of them all: lead.

In December 1921, Midgley's team in Dayton concocted enough of the compound tetraethyl lead to do a test run with a kerosene-powered engine suffering from a serious case of engine knock. A single teaspoon of tetraethyl lead silenced the knock completely. Further tests revealed that you could subdue engine knock with a shockingly small supplement of lead; they ultimately settled on a lead-to-gasoline ratio of 1-to-1,300. The effects on engine performance were profound. Automobiles running on leaded gasoline could take on steep inclines without hesitation; drivers could accelerate to overtake a slower vehicle on a two-lane road without worrying about their engine being seized with knock while in the wrong lane.

Kettering branded the new fuel Ethyl, and in February 1923 it was first offered for sale at a gas station in downtown Dayton. By 1924, General Motors, the DuPont Corporation and Standard Oil had started a joint venture called the Ethyl Corporation to produce the gasoline at scale, with Kettering and Midgley appointed as executives. Henry Ford's assembly-line production of the original Model T in 1908 is usually credited as the point of origin for the American love affair with the automobile, but the introduction of high-octane Ethyl gasoline was instrumental as well. Over the course of the 1920s, the number of registered vehicles in the United States tripled. By the end of the decade, Americans owned close to 80 percent of all the automobiles in the world, increasingly powered by the miraculous new fuel that Thomas Midgley concocted in his lab.

A few years after the triumph of Ethyl, Kettering and Midgley turned to another revolutionary technology, soon to be as ubiquitous in American culture as the automobile: electric refrigeration. Generating heat through artificial means had a long and illustrious history, from the mastery of fire to the steam engine to the electric stove. But no one had approached the problem of keeping things cold with technological solutions until the late 1800s. For most of the 19th century, if you wanted to refrigerate something, you bought ice that had been carved out of a frozen lake in a northern latitude during the winter and shipped to some warmer part of the world. (Ice was a major export item for American commerce during that period, with frozen lake ice from New England shipped as far as Brazil and India.) But by the end of the century, scientists and entrepreneurs began to experiment with artificial cold. Willis Carrier designed the first air-conditioning system for a printing house in Brooklyn in 1902; the first electric-powered home refrigerators appeared a decade later. In 1918, two years after Midgley started working for Kettering, General Motors acquired a home-refrigerator start-up and gave it a brand name that lives on to this day: Frigidaire.

But as with the automobile in the engine-knock era, the new consumer technology of refrigeration was being held back by what was effectively a problem of chemistry. Creating artificial cold required some kind of gas to be used as a refrigerant, but all the available compounds in use were prone to catastrophic failure. During the 1893 World's Fair in Chicago, an industrial-scale ice-manufacturing plant exploded, killing 16 people, when the ammonia it was using as a refrigerant ignited. Another popular refrigerant, methyl chloride, had been implicated in dozens of deaths around the country, the victims of accidental leaks. Frigidaire's products relied on sulfur dioxide, a toxic gas that could cause nausea, vomiting, stomach pain and damage to the lungs.

With newspaper headlines denouncing the "death gas ice boxes" and a growing number of legislators exploring the idea of banning home refrigerators outright, Kettering turned to Midgley to come up with a solution. One day in 1928, as Midgley later recalled, "I was in the laboratory and called Kettering in Detroit about something of minor importance. After we'd finished this discussion, he said: 'Midge, the refrigeration industry needs a new refrigerant if they ever expect to get anywhere.'" Kettering announced that he was dispatching a Frigidaire engineer to visit Midge in the lab the next day to brief him on the challenge.

Once again, Midgley turned to his nonstandard periodic table, this time using a technique he had come to call the "fox hunt," which proved to be far more efficient than the random walk he employed in the engine-knock investigation. He began with the observation that most elements that remained gaseous at low temperatures — a key for refrigeration — were located on the right side of the table, including elements like sulfur and chlorine that were already in use. That first step narrowed the search considerably. Midgley then eliminated a number of neighboring elements out of hand for either being too volatile or having a suboptimal boiling point.

Then he found the one element not yet being used in commercial refrigerants: fluorine. Midgley knew that fluorine on its own was highly toxic — its primary industrial use was as an insecticide — but he hoped to combine the gas with some other element to make it safer. Within a matter of hours, Midgley and his team hit upon the idea of mixing fluorine with chlorine and carbon, developing a class of compound that would come to be called chlorofluorocarbons, or CFCs for short. Subsequent tests revealed — as Kettering would put it years later in his eulogy for Midgley — that their compound was "highly stable, noninflammable and altogether without harmful effects on man or animals." Shortly after, General Motors entered into a partnership with DuPont to manufacture the compound at scale. By 1932 they had registered a new trademark for the miracle gas: Freon.

We live under the gathering storm of modern history's most momentous unintended consequence: carbon-based climate change.

Freon arrived just in the nick of time for the refrigeration industry. In July 1929, a methyl-chloride leak of "ice machine gas" in Chicago killed 15 people, raising even more concerns about the safety of existing refrigerants. Ever the showman, Midgley performed an act worthy of a vaudeville magician onstage at the national meeting of the American Chemical Society in 1930, inhaling a cloud of the gas and then exhaling to blow out a candle — thus demonstrating Freon's nontoxicity and its nonflammability. Frigidaire leaned hard into the safety angle in the advertising for its new Freon-powered refrigerator line, announcing that the "Pursuit of Health and Safety Led to the Discovery of Freon." By 1935, eight million refrigerators using Freon had been sold, and Willis Carrier had employed the gas to create a new home air-conditioning unit called the "atmospheric cabinet." Artificial cold was well on its way to becoming a central part of the American dream.

Soon, Midgley's miracle gas would find a new use in consumer goods — one that ultimately became even more dangerous to the environment than its use as a refrigerant. In 1941, two chemists at the Department of Agriculture, one of whom formerly worked for DuPont, invented a device to disperse insecticide in a fine mist, using a variation of Midgley's original concoction called Freon-12 as the aerosol propellant. After malaria deaths contributed to the fall of the Philippines in 1942, the U.S. military ramped up production of "bug bombs" to protect troops from insect-borne diseases, ultimately giving birth to an entire aerosol industry, which used Freon to disperse everything from DDT to hair spray. The new utility seemed, at the time, to be yet another example of "better living through chemistry," as DuPont's corporate slogan put it. "A double delight is dichlorodifluoromethane, with its thirteen consonants and ten vowels," The Times wrote. "It brings death to disease-carrying insects and provides cool comfort to man when July and August suns bake city pavements. This wonder gas is popularly known as Freon 12."

Two innovations — Ethyl and Freon, conjured by one man presiding over a single laboratory during a span of roughly 10 years. Combined, the two products generated billions of dollars in revenue for the companies that manufactured them and provided countless ordinary consumers with new technology that improved the quality of their lives. In the case of Freon, the gas enabled another technology (refrigeration) that offered meaningful improvements to consumers in the form of food safety. And yet each product, in the end, turned out to be dangerous on an almost unimaginable scale.

The history of any major technological or industrial advance is inevitably shadowed by a less predictable history of unintended consequences and secondary effects — what economists sometimes call "externalities." Sometimes those consequences are innocuous ones, or even beneficial. Gutenberg invents the printing press, and literacy rates rise, which causes a significant part of the reading public to require spectacles for the first time, which creates a surge of investment in lens-making across Europe, which leads to the invention of the telescope and the microscope. Oftentimes the secondary effects seem to belong to an entirely different sphere of society. When Willis Carrier hit upon the idea of air-conditioning, the technology was primarily intended for industrial use: ensuring cool, dry air for factories that required low-humidity environments. But once air-conditioning entered the home — thanks in part to Freon's radical leap forward in safety — it touched off one of the largest migrations in the history of the United States, enabling the rise of metropolitan areas like Phoenix and Las Vegas that barely existed when Carrier first started tinkering with the idea in the early 1900s.

Sometimes the unintended consequence comes about when consumers use an invention in a surprising way. Edison famously thought his phonograph, which he sometimes called "the talking machine," would primarily be used to take dictation, allowing the masses to send albums of recorded letters through the postal system; that is, he thought he was disrupting *mail*, not music. But then later innovators, like the Pathé brothers in France and Emile Berliner in the United States, discovered a much larger audience willing to pay for musical recordings made on descendants of Edison's original invention. In other cases, the original innovation comes into the world disguised as a plaything, smuggling in some captivating new idea in the service of fun that spawns a host of imitators in more upscale fields, the way the animatronic dolls of the mid-1700s inspired Jacquard to invent the first "programmable" loom and Charles Babbage to invent the first machine that fit the modern definition of a computer, setting the stage for the revolution in programmable technology that would transform the 21st century in countless ways.

We live under the gathering storm of modern history's most momentous unintended consequence, one that Midgley and Kettering also had a hand in: carbon-based climate change. Imagine the vast sweep of inventors whose ideas started the Industrial Revolution, all the entrepreneurs and scientists and hobbyists who had a hand in bringing it about. Line up a thousand of them and ask them all what they had been hoping to do with their work. Not one would say that their intent had been to deposit enough carbon in the atmosphere to create a greenhouse effect that trapped heat at the surface of the planet. And yet here we are.

Ethyl and Freon belonged to the same general class of secondary effect: innovations whose unintended consequences stem from some kind of waste byproduct that they emit. But the potential health threats of Ethyl were visible in the 1920s, unlike, say, the long-term effects of atmospheric carbon buildup in the early days of the Industrial Revolution. The dark truth about Ethyl is that everyone involved in its creation had seen incontrovertible evidence that tetraethyl lead was shockingly harmful to humans. Midgley himself experienced firsthand the dangers of lead poisoning, thanks to his work in Dayton developing Ethyl in the lab. In early 1923, Midgley cited health reasons in declining an invitation to a gathering of the American Chemical Society, where he was supposed to receive an honor for his latest discovery. "After about a year's work in organic lead," he wrote to the organization, "I find that my lungs have been affected and that it is necessary to drop all work and get a large supply of fresh air." In a jaunty note to a friend at the time, Midgley wrote: "The cure for said ailment is not only extremely simple but quite delightful. It means to pack up, climb a train and search for a suitable golf course in the state named Florida."

Freon, invented in 1928 as a refrigerant, helped turn Frigidaire into a household name. Decades later, scientists realized that Freon and other chlorofluorocarbons were creating a dangerous hole in the ozone layer. Archive Photos/Getty Images

Midgley did in fact recover from his bout with lead poisoning, but other early participants in the Ethyl business were not so lucky. Days after the first mass-production site for tetraethyl lead opened at DuPont's Deepwater facility in New Jersey, Midgley and Kettering found themselves responsible for one of the most horrifying chapters in the history of industrial-age atrocities. On the eastern banks of the Delaware River, not far from DuPont's headquarters in Wilmington, the Deepwater facility already had a long history of industrial accidents, including a series of deadly explosions in its original operational role of manufacturing gunpowder. But as soon as it began producing Ethyl at scale, the factory turned into a madhouse. "Eight workers in the DuPont tetraethyl gas plant at Deep Water, near Penns Grove, N.J., have died in delirium from tetraethyl lead poisoning in 18 months and 300 others have been stricken," The Times would later write in an investigative report. "One of the early symptoms is a hallucination of winged insects. The victim pauses, perhaps while at work or in a rational conversation, gazes intently at space and snatches at something not there." Eventually, the victims would descend into violent, self-destructive insanity. One worker threw himself off a ferry in a suicide attempt; another jumped from a hospital window. Many had to be placed in straitjackets or strapped to their beds as they convulsed in abject terror. Before work was halted at the plant, the hallucinations of swarming insects became so widespread that the five-story building where Ethyl was produced was called the "house of butterflies."

Perhaps the most damning evidence against Midgley and Kettering lies in the fact that both men were well aware that at least one potential alternative to tetraethyl lead existed: ethanol, which had many of the same antiknock properties as lead. But as Jamie Lincoln Kitman notes in "The Secret History of Lead": "GM couldn't dictate an infrastructure that could supply ethanol in the volumes that might be required. Equally troubling, any idiot with a still could make it at home, and in those days, many did." On the face of it, ethyl alcohol would have seemed the far safer option, given what was known about lead as a poison and the unfolding tragedies at Deepwater and other plants. But you couldn't *patent* alcohol.

In May 1925, the surgeon general formed a committee to investigate the health hazards of Ethyl, and a public hearing was held. Kettering and other industry figures spoke, squaring off against a cadre of physicians and scholars. The following January, the committee officially found that there was no conclusive evidence of risk to the general public in the use of leaded gasoline. Within weeks, the factories were back online, and within a decade, Ethyl was included in 90 percent of all gasoline sold in America.

The first real clue of leaded gasoline's true environmental impact came out of one of the 20th century's most fabled accidental discoveries. In the late 1940s, the geochemist Clair Patterson embarked on an ambitious project with colleagues at the University of Chicago to establish a more accurate account of Earth's true age, which at that point was generally considered to be just over three billion years. Patterson's approach analyzed the small amounts of uranium contained in the mineral zircon. Zircon in its initial state is free of lead, but uranium produces lead at a steady rate as it decays. Patterson assumed that measuring the ratios of various lead isotopes in a given sample of zircon would give him a precise age for the zircon, an important first step in his quest to calculate the true age of Earth itself. But Patterson quickly found that the measurements were almost impossible to make — because there was far too much ambient lead in the atmosphere to get an accurate reading.

Eventually, after a move to the California Institute of Technology several years later, Patterson built an elaborate "clean room," where he was able to make enough uncontaminated measurements to prove that Earth was a billion years older than previously thought. But his battle with lead contamination in the lab also sent him on a parallel journey, to document the enormous quantities of lead that had settled over every corner of the planet in the modern era. Analyzing ice-core samples from Greenland, he found that lead concentration had increased fourfold over the first two centuries of industrialization. The short-term trends were even more alarming: In the 35 years that had passed since Ethyl gasoline became the standard, lead concentrations in polar ice cores had risen by 350 percent. Other investigators, like the Philadelphia doctor Herbert Needleman, published studies in the 1970s suggesting that even low levels of lead exposure could cause significant cognitive defects in young children, including lowered I.Q. scores and behavioral disorders.

Patterson and Needleman were pilloried for their findings by the automobile and lead industries, but as the scientific evidence began to pile up, a consensus finally emerged that leaded gasoline had turned out to be one of the most harmful pollutants of the 20th century, one that proved to be especially concentrated in urban areas. Globally, the phaseout of leaded gasoline that began in the 1970s is estimated to have saved 1.2 million lives a year. As Achim Steiner of the United Nations noted, "The elimination of leaded petrol is an immense achievement on par with the global elimination of major deadly diseases."

The realization that CFCs were harming the environment began the same way the understanding of lead's impact began: with a new technology for measurement, namely a contraption known as an electron-capture detector. Invented in the late 1950s by James Lovelock — a British scientist who would gain fame more than a decade later by formulating the "Gaia hypothesis" — this device could measure minute concentrations of gases in the atmosphere with far more precision than had yet been possible. In some of his early observations with the device, Lovelock discovered a surprisingly large quantity of CFCs, with more of them circulating in the atmosphere above the Northern Hemisphere than above the Southern.

Lovelock's findings piqued the interest of the chemists Sherwood Rowland and Mario Molina, who made two alarming discoveries in the mid-1970s: first, the fact that CFCs had no natural "sinks" on Earth where the chemical could be dissolved, which meant that all CFCs emitted through human activity would eventually settle in the upper atmosphere; and second, the fact that at those high altitudes, the intense ultraviolet light from the sun would cause them to finally break down, releasing chlorine that did substantial damage to the ozone layer. Shortly after Rowland and Molina published their work, evidence emerged that ozone levels were depleted in the stratosphere above the South Pole; a daring high-altitude flight overseen by the atmospheric chemist Susan Solomon eventually proved that the "hole" in the ozone layer had been caused by the human-created CFCs that Thomas Midgley concocted in his lab more than 50 years earlier.

As with the fight over leaded gasoline, the industries involved in CFC production resisted efforts to reduce the presence of the gas in the atmosphere, but by the late 1980s, the evidence of potential harm had grown undeniable. (Unlike in the current debate over global warming, no mainstream political constituency emerged to challenge this consensus, other than the industry players who had a financial stake in continued CFC production.) In September 1987, representatives of 24 nations signed the Montreal Protocol on Substances That Deplete the Ozone Layer, establishing a timetable for the world to phase out production and consumption of CFCs, almost 60 years after Kettering told Midgley to figure out a solution to the refrigerant problem. It took a small team just a few days in a lab to address Kettering's problem, but it took a global collaboration of scientists, corporations and politicians to repair the damage that their creation inadvertently unleashed on the world.

Based on Rowland's original research in the 1970s, the National Academy of Sciences estimated that continued CFC production at the same rate would destroy 50 percent of the ozone layer by 2050. About a decade ago, an international team of climate scientists created a computer model to simulate what would have happened if the Montreal Protocol had not been put into effect. The results were even more disturbing than previously forecast: By 2065, nearly two-thirds of the ozone layer would have disappeared. In mid-latitude cities like Washington and Paris, just five minutes of exposure to the sun would have been enough to give you sunburn. Skin-cancer rates would have skyrocketed. A 2021 study by scientists at Lancaster University looked at the impact that continued CFC production would have had on plant life. The additional UV radiation would have greatly diminished the absorption of carbon dioxide through photosynthesis, creating an additional 0.8 degrees Celsius of global warming, on top of the increased temperature caused by fossil-fuel use.

In his 2020 book on existential risk, "The Precipice," the Oxford philosopher Toby Ord tells the story of a concern, initially raised by the physicist Edward Teller in the months leading up to the first detonation of a nuclear device, that the fission reaction in the bomb might also ignite a fusion reaction in the surrounding nitrogen in Earth's atmosphere, thus "engulfing the Earth in flame … and [destroying] not just humanity, but all complex life on Earth." Teller's concerns touched off a vigorous debate among the Manhattan Project scientists about the likelihood of an unintended atmospheric chain reaction. Ultimately, they decided that the world-engulfing firestorm was not likely to happen, and the Trinity Test went ahead as planned at 5:29 a.m. local time on the morning of July 16, 1945. Teller's fears proved to be unfounded, and in the hundreds of nuclear detonations since, no apocalyptic atmospheric chain reactions have been unleashed. "Physicists with a greater understanding of nuclear fusion and with computers to aid their calculations have confirmed that it is indeed impossible," Ord writes. "And yet, there *had* been a kind of risk."

Ord dates the genesis of what he calls the Precipice — the age of existential risk — to that July morning in 1945. But you could make the argument that a better origin point might well be that afternoon in 1928, when Thomas Midgley Jr. and his team fox-hunted their way across the periodic table to the development of chlorofluorocarbons. Teller, after all, was wrong about his imagined chain-reaction apocalypse. But CFCs actually did produce a chain reaction in the atmosphere, one that left unabated might well have transformed life on Earth as we know it. Whether Freon was "altogether without harmful effects on man or animals," as Kettering once claimed, depended on the time scale you used. On the scale of years and decades, it most likely saved many lives: keeping food from spoiling, allowing vaccines to be stored and transported safely, reducing malaria deaths. On the scale of a century, though, it posed a significant threat to humanity itself.

Indeed, it is reasonable to see CFCs as a forerunner of the kind of threat we will most likely face in the coming decades, as it becomes increasingly possible for individuals or small groups to create new scientific advances — through chemistry or biotechnology or materials science — setting off unintended consequences that reverberate on a global scale. The dominant models of technological apocalypse in the 20th century were variations on the Manhattan Project: industrial-scale, government-controlled weapons of mass destruction, designed from the outset to kill in large numbers. But in the 21st century, the existential threats may well come from innovators working in Midgley's mode, creating new dangers through the seemingly innocuous act of addressing consumer needs, only this time using CRISPR, or nanobots, or some new breakthrough no one has thought of yet.

All of which makes it essential to ask the question: Was it possible for Midgley (and Kettering) to have swerved away from the precipice and not have unleashed such destructive forces into the world? And have we built new defenses since then that are sufficient to prevent some 21st-century Midgley from inflicting equivalent damage on the planet, or worse? The answers to those questions turn out to be very different, depending on whether the innovation in question is Ethyl or Freon. Leaded gasoline, which in the end did far more harm to human health than CFCs, was actually a more manageable and preventable class of threat. What should keep us up at night is the modern-day equivalent of CFCs.

In the end, leaded gasoline was a mistake of epic proportions, but it was also a preventable mistake. The rise of Ethyl was an old story: a private company's reaping profits from a new innovation while socializing the costs of its unintended consequences and overriding the objections at the time through sheer commercial might. It was well established that lead was a health hazard; that the manufacture of Ethyl itself could have devastating effects on the human body and brain; that automobiles running on Ethyl were emitting some trace of lead into the atmosphere. The only question was whether those trace amounts could cause health problems on their own.

The question of leaded gasoline's health risks to the general public was a known unknown. The health risk posed by Freon was a more mercurial beast: an unknown unknown.

Since the surgeon general's hearing in 1926, we have invented a vast array of tools and institutions to explore precisely these kinds of questions before a new compound goes on the market. We have produced remarkably sophisticated systems to model and anticipate the long-term consequences of chemical compounds on both the environment and individual health. We have devised analytic and statistical tools — like randomized controlled trials — that can detect subtle causal connections between a potential pollutant or toxic chemical and adverse health outcomes. We have created institutions, like the Environmental Protection Agency, that try to keep 21st-century Ethyls out of the marketplace. We have laws like the Toxic Substances Control Act of 1976 that are supposed to ensure that new compounds undergo testing and risk assessment before they can be brought to market. Despite their limitations, all of these things — the regulatory institutions, the risk-management tools — should be understood as innovations in their own right, ones that are rarely celebrated the way consumer breakthroughs like Ethyl or Freon are. There are no ad campaigns promising "better living through deliberation and oversight," even though that is precisely what better laws and institutions can bring us.

The story of Freon offers a more troubling lesson, though. Scientists had observed by the late 19th century that there seemed to be a puzzling cutoff in the spectrum of radiation hitting Earth's surface, and soon they suspected that ozone gas was somehow responsible for that "missing" radiation. The British meteorologist G.M.B. Dobson undertook the first large-scale measurements of the ozone layer in 1926, just a few years before Kettering and Midgley started exploring the problem of stable refrigerants. Dobson's investigations took decades to evolve into a comprehensive understanding. (Dobson did all his work from ground-level observations. No human had even visited the upper atmosphere before the Swiss scientist and balloonist Auguste Piccard and his assistant ascended to 52,000 feet in a sealed gondola in 1931.) The full scientific understanding of the ozone layer itself wouldn't emerge until the 1970s. Unlike with Ethyl, where there was a clear adverse relationship on the table between lead and human health, no one even considered that there might be a link between what was happening in the coils of your kitchen fridge and what was happening 100,000 feet above the South Pole. CFCs began inflicting their harm almost immediately after Freon hit the market, but the science capable of understanding the subtle atmospheric chain reactions behind that harm was still 40 years in the future.

Is it possible that we are doing something today whose long-term unintended consequences will not be *understandable to science* until 2063? That there are far fewer blank spots on the map of understanding is unquestionable. But the blank spots that remain are the ones capturing all the attention. We have already made some daring bets at the edges of our understanding. While building particle accelerators like the Large Hadron Collider, scientists seriously debated the possibility that activating the accelerator would trigger the creation of tiny black holes that would engulf the entire planet in seconds. It didn't happen, and there was substantial evidence that it would not happen before they flipped the switch. But still.

As the scenario planners put it, the question of leaded gasoline's health risks to the general public was a *known unknown*. We knew there was a legitimate question that needed answering, but big industry just steamrollered over the whole investigation for almost half a century. The health risk posed by Freon was a more mercurial beast: an *unknown unknown*. There was no way of answering the question — are CFCs bad for the health of the planet? — in 1928, and no real hint that it was even a question worth asking. Have we gotten better at imagining those unimaginable threats? It seems possible, maybe even likely, that we have, thanks to a loose network of developments: science fiction, scenario planning, environmental movements and, recently, the so-called longtermists, among them Toby Ord. But blank spots on the map of understanding are blank spots. It's hard to see past them.

This is where the time-horizon question becomes essential. The longtermists get a lot of grief for focusing on distant sci-fi futures — and ignoring our present-day suffering — but from a certain angle, you can interpret the Midgley story as rebuttal to those critics. Saturating our inner cities with toxic levels of ambient lead for more than half a century was a terrible idea, and if we had been thinking about that decades-long time horizon back in 1923, we might have been able to make another choice — perhaps embracing ethanol instead of Ethyl. And the results of that longtermism would have had a clear progressive bias. The positive impact on low-income, marginalized communities would have been far greater than the impact on affluent entrepreneurs tending to their lawns in the suburbs. If you gave a present-day environmental activist a time machine and granted them one change to the 20th century, it's hard to imagine a more consequential intervention than shutting down Thomas Midgley's lab in 1920.

But the Freon story suggests a different argument. There was no use expanding our time horizon in evaluating the potential impact of CFCs, because we simply didn't have the conceptual tools to do those calculations. Given the acceleration of technology since Midgley's day, it's a waste of resources to try to imagine where we will be 50 years from now, much less 100. The future is simply too unpredictable, or it involves variables that are not yet visible to us. You can have the best of intentions, running your long-term scenarios, trying to imagine all the unintended secondary effects. But on some level, you've doomed yourself to chasing ghosts.

The acceleration of technology casts another ominous shadow on Midgley's legacy. Much has been made of his status as a "one-man environmental disaster," as The New Scientist has called him. But in actuality, his ideas needed an enormous support system — industrial corporations, the United States military — to amplify them into world-changing forces. Kettering and Midgley were operating in a world governed by linear processes. You had to do a lot of work to produce your innovation at scale, if you were lucky enough to invent something worth scaling. But much of the industrial science now exploring the boundaries of those blank spots — synthetic biology, nanotech, gene editing — involves a different kind of technology: things that make copies of themselves. Today the cutting-edge science of fighting malaria is not aerosol spray cans; it's "gene drive" technology that uses CRISPR to alter the genetics of mosquitoes, allowing human-engineered gene sequences to spread through the population — either reducing the insects' ability to spread malaria or driving them into extinction. The giant industrial plants of Midgley's age are giving way to nanofactories and biotech labs where the new breakthroughs are not so much manufactured as they are grown. A recent essay in The Bulletin of the Atomic Scientists estimated that there are probably more than 100 people now with the skills and technology to single-handedly reconstruct an organism like the smallpox virus, Variola major, perhaps the greatest killer in human history.

It is telling that the two moments when we stood on the very edge of Toby Ord's "precipice" in the 20th century involved chain reactions: the fusion reaction set off by the Trinity Test and the chain reaction set off by CFCs in the ozone layer. But self-replicating organisms (or technologies) pose a different order of risk — exponential risk, not linear — whether they are viruses engineered by gain-of-function research to be more lethal, venturing into the wild through a lab leak or a deliberate act of terrorism, or a runaway nanofactory producing microscopic machines for some admirable purpose that escapes the control of its creator.

In his 2015 book, "A Dangerous Master: How to Keep Technology From Slipping Beyond Our Control," Wendell Wallach talks about the class of unsettling near-term technologies that generally fit under the umbrella of "playing God": cloning, gene editing, "curing" death, creating synthetic life-forms. There is something unnervingly godlike in the sheer scale of the impact that Thomas Midgley Jr. had on our environment, but the truth is that his innovations required immense infrastructure, all those Ethyl and Freon factories and gas stations and aerosol cans, to actually bring about that long-term destruction. But today, in an age of artificial replicators, it is much easier to imagine a next-generation Midgley playing God in the lab — with good or evil intent — and dispatching his creations with that most ancient of commands: *Go forth, and multiply.*

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***Corrections were made on March 17, 2023**: An earlier version of this article referred incorrectly to ammonia. It is a compound, not an element.*

An earlier version of this article mischaracterized a concern raised by Edward Teller about the detonation of the first nuclear device during the Trinity Test. The concern was that a fission reaction, not a fusion reaction, within the bomb would trigger a fusion reaction in the atmosphere.

An earlier version of this article misstated the location of fluorine in a nonstandard periodic table of elements that Thomas Midgley used. It is not on the bottom right corner.

A version of this article appears in print on , Page 36 of the Sunday Magazine with the headline: The Man Who Broke the World