LONG HARD ROAD

The Lithium-Ion Battery and the Electric Car

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Purdue University Press / West Lafayette, Indiana

Printed in the United States of America.

Cataloging-in-Publication Data is on file with the Library of Congress.
978-1-61249-762-4 (hardback)
978-1-61249-763-1 (epub)
978-1-61249-764-8 (epdf)

This book was generously supported by a grant from the Alfred P. Sloan Foundation.

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For Pat, my trusted reader and best friend

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Preface

In popular culture, the battery-powered car is a new idea.

But the truth is that the battery-powered car is by no means new. It's been with us for more than a century, starting in 1884, when English inventor Thomas Parker developed the first manufacturable electric vehicle. It enjoyed some success back then, making up approximately 38 percent of the vehicles on US roads by 1900. Interest in it was widespread, and many notable inventors of the day tried to improve it, including Thomas Edison and Henry Ford, who collaborated on an EV powered by a nickel–iron battery in 1913.

Similarly, the rechargeable lithium battery is not a new idea. By the time this book reaches publication in the fall of 2022, the rechargeable lithium battery will be celebrating its fiftieth birthday. Many of those birthdays occurred beneath the popular culture radar; indeed, nineteen years passed before it finally reached commercial production. But it has been in existence for all those years, if not always in full view.

Thus, it could be accurately stated that the story of the lithium-ion battery and the electric car is not one of overnight success. It is not about a single eureka moment. It is, rather, a story of long-term commitment—commitment by scientists and engineers to an old idea with an uncertain future. And that's what makes it so remarkable. The rechargeable lithium battery came to the world not as a single entity, but as a succession of parts. First, as a cathode; then, an anode; and finally, a full working product. It came from different creators working independently on four different continents over many years. And it was not until it had proven itself in the electronics arena that it began gaining traction in the auto industry, where the battery-powered car had to contend with a long history of disappointments. Yet, it prevailed.

This book attempts to capture some of the breadth and the struggles associated with that history. It follows the lithium-ion battery's evolution from Detroit to California to New Jersey to Oxford to Japan. Then it tracks the battery's uneasy automotive adoption from Japan to a California garage shop and, finally, back to Detroit.

It is a complicated story. There are many players, many battery chemistries, and many dead ends. Thus, readers would be well-served to use the references in this book—the timeline at the beginning, as well as the glossary and who's who at the end.

Our story ends with the awarding of the Nobel Prize in Chemistry in 2019. But even as our tale stops there, the real-world saga continues to change with every passing week. Therefore, it should be understood that we have by no means reached the final chapter of this technology's evolution.

The world described in the pages that follow is really only the beginning.

Charles J. Murray
April 2022

Prologue: An Idea in the Air

When the Nobel Prize in Chemistry was awarded to three scientists in 2019 for the invention of the lithium-ion battery, much of the world assumed it was another instance of a few inventors conjuring up a great idea, then cashing in. That, of course, was the twenty-first-century scenario to which the world had grown accustomed in tech entrepreneurs like Bill Gates, Steve Jobs, Jeff Bezos, Elon Musk, and others.

But it wasn't the case. The lithium-ion battery was not the product of a single mind, nor did it yield instant riches. The unromantic truth was that it was a quarter-century effort that took place in dozens of labs around the world. And it relied on the most old-fashioned of pre-Internet networking techniques—papers in scientific journals and technical presentations on overhead projectors in hotel conference rooms. The result was a collection of independent micro-innovations that migrated from one chemist to another, from one conference to another, to labs on four different continents, thousands of miles apart.

It was, in essence, an idea in the air, and it spread like a virus through the scientific community starting in the 1970s. In the beginning, there were a few dozen scientists, then a few hundred, a few thousand, and then tens of thousands. The battery's component parts were invented at different times, by different people, in different places. Some of the inventions fell into a category that science historians call "multiples"—that is, identical ideas occurring simultaneously in different parts of the world. The graphite anode was such a case. Scientists in France, Germany, Japan, and the United States made very similar discoveries in a period of two years. Similarly, the nickel manganese cobalt cathode involved four independent breakthroughs in different locales around the world, all in a single year. There was, of course, historical precedent for such parallel phenomena. As author Malcolm Gladwell has notably pointed out,[1] there are many such multiples throughout the course of scientific history. Leibniz and Newton invented calculus independently and simultaneously in different countries; Alexander Graham Bell and Elisha Gray independently filed for patents for the telephone on the same day. And there were many others. Like calculus and the telephone, the lithium-ion battery was a product of the intellectual climate of the day.

The simplified story behind lithium-ion is that it had been an archetype of the linear development process—that it was born of fundamental research, then moved to applied research and, finally, graduated to engineering. In truth, though, it was far more chaotic than that. The impetus for what would later become the lithium-ion battery had actually come from Detroit, from a small band of scientists at Ford Motor Company studying what they called fast ion transport. It had then zigzagged back and forth from applied to fundamental research, from California to New Jersey to England to France, before moving on to engineering in Japan. There was nothing linear about it.

In the beginning, few had given the technology much of a chance. John Goodenough, inventor of the first two lithium-ion cathodes, had been ignored when he'd tried to market his idea. His own university refused to pay for patenting. So his discovery languished for years.

If not for the Japanese, the battery probably would have remained little more than a technical curiosity for at least another decade, and maybe longer. But Japanese engineers recognized it as a power source for camcorders and laptop computers, and so they marshaled their efforts and brought it to market. Their role, often underappreciated in the US and Europe, was absolutely essential.

Even then, their path to success was anything but smooth. For many years, there would be a revisionist version of the battery's journey to market in Japan. But this version was woefully short on detail. In reality, the journey started with a company that didn't fully comprehend the value of its own invention. Nor did that company know how to manufacture it, so two of its engineers took their chemistry experiment to a converted truck garage in Boston, Massachusetts, where the first two hundred preproduction cells were built. Only then did the concept gain momentum, thanks to a competitor in Japan who brought more knowledge and infinitely more resolve.

It finally reached the market in 1991, twenty-five years after the Ford Motor Company had built the first fast-ion-transport battery. And by that time, it seemed to be an invention from another era. It was as if a giant unseen hand had scooped up a nineteenth-century innovation and dropped it into the twentieth. It was not a software product, nor a semiconductor material, and it did not obey Moore's Law—which is to say that its cost did not drop by half every eighteen months.

Moreover, it did not come from the mind of a single postadolescent billionaire. There was no eureka moment nor a tale of overnight success. As an invention, it was a closer cousin to the internal combustion engine than to the digital computer.

When it ultimately emerged from its chemistry lab cocoon in 1991, its history became more public. The world watched as it moved from success to success, from camcorders to laptop computers to cell phones. It watched as the battery's production volumes climbed into the billions of cells per year, and then as it magically appeared on the shelves of grocery stores. It was only then that the world asked if lithium-ion chemistry might solve the longstanding, seemingly insoluble problem of the electric car.

By the time the lithium-ion pioneers won the Nobel, sales of lithium-ion batteries had already reached $30 billion a year and were climbing fast. The batteries were everywhere—cell phones, cameras, tablets, laptops, snowblowers, lawn mowers, and electric bikes. And with the growth of the electric car, the lithium-ion market was poised to get much, much bigger.

That was why so many people had trouble comprehending the fact that the Nobel winners never enjoyed a big payday. Especially in the United States, consumers had come to believe that virtually all new technology was the product of entrepreneurial spirit, and that all inventors were founders of start-ups and were therefore inconceivably wealthy. But the inventors of lithium-ion were none of those things. Moreover, it is one of the singularly strange aspects of the lithium-ion story that the creators had no clue as to the eventual impact of their invention.

Decades after John Goodenough had invented his cathode, and had given up on trying to convince the world of its value, people still seemed to have trouble understanding how he couldn't have had more confidence in something so astonishingly valuable. For the rest of his life they would ask, Didn't you know? Didn't you anticipate the value of the technology? "I said, 'Of course not,'" Goodenough later stated. "I didn't know they were going to be worth billions."[2]

Neither did anyone else.

Timeline of Events

Battery	Automobile
1800 Alessandro Volta invents voltaic pile	
1859 Gaston Planté invents rechargeable lead–acid battery	
	1884 Thomas Parker develops first manufacturable electric vehicle (in UK)
	1900 38% of cars are electric
1901 Thomas Edison invents rechargeable nickel–iron battery	
	1912 Charles Kettering invents "crankless" self-starter for gasoline cars
	1913 Edison teams with Henry Ford on EV
	1914 Edison–Ford EV partnership ends
1963 Ford Motor begins work on sodium–sulfur battery	
1972 Stanley Whittingham invents lithium intercalation battery at Exxon	
1980 John Goodenough invents lithium cobalt oxide cathode	
1981 Michael Thackeray, Goodenough invent lithium manganese oxide cathode	

Continued

Battery	Automobile
1986 Asahi Chemical develops rechargeable lithium battery with soft carbon anode	
1986 Ovonic patents nickel–metal hydride battery	
1986 Asahi Chemical builds preproduction batteries in Boston	
1990 Sony announces first commercial lithium-ion battery	
1993 Sanyo rolls out lithium-ion battery with graphite anode	**1993** Ford debuts Ecostar EV with sodium–sulfur battery
	1996 GM introduces EV1 electric car with lead–acid battery
1997 Goodenough publishes paper about lithium iron phosphate battery	
	1998 GM's EV1 switches to nickel–metal hydride battery
	1998 Nissan debuts first lithium-ion-based electric car, the Altra EV
2000 Development of lithium NMC battery	
	2003 AC Propulsion builds Tzero EV using 6,800 lithium-ion cells
	2009 Tesla Motors rolls out Roadster EV with 6,831 lithium-ion cells
	2010 Nissan unveils Leaf EV with lithium-ion battery
2019 Goodenough, Whittingham, Akira Yoshino win Nobel Prize for invention of lithium-ion battery	

Part I

The Making of a Battery

"Inventing is a combination of brains and materials—the more the brains, the less the material."

CHARLES F. KETTERING, AMERICAN INVENTOR AND ENGINEER

1

The Fast-Ion Concept

It began as a simple request. Joe Kummer wanted a few discs to be made from a glassy material called beta alumina.

The other scientists at Ford Motor Company's Research and Engineering Center assumed Kummer wanted the discs for a battery. He'd been talking for more than a year with another Ford scientist, Neill Weber, about the ionic conductivity of beta alumina. Together, they created a few loose samples of it and discussed employing it in an electric car.

On its surface, the idea sounded a bit far-fetched. But this was Ford's research lab. There was nothing wrong with a bit of creative thinking in the research lab. Besides, this was Joe Kummer, and no one at Ford questioned his scientific ability. The gears in Kummer's brain always seemed to be churning, working on some new and unseen problem. He frequently combed through technical journals at the Ford library, making discoveries, coming up with new ideas, then telling colleagues about them. Even at home, his creativity was nonstop. Atop his living room television set there was a broomstick attached to a wooden frame that held multiple rabbit ears to receive TV signals from the north, south, east, and west.[1] He outfitted the contraption with electrical switches to scroll through the best signals, and it worked. His sense of scientific joy was almost childlike. He would take an orange or a lemon, jab a couple of makeshift electrodes in it, and use it to illuminate a tiny light bulb. Then he would display it on his desk, like a trophy.

He was no one's idea of a prototypical scientist. At six feet, eight inches tall[2] with huge hands and size fifteen shoes, Kummer looked like a basketball player in a lab coat. He towered over his colleagues, but had a soft voice and a gentle disposition. No one at the lab had ever seen him get mad. He was not considered intimidating. He loved working at his lab bench, detested administrative work, and didn't care to move up to management. He had earned a PhD in chemical engineering from Johns Hopkins University and was happy being a scientist.

So it was on this day in the late summer of 1963 that when he suggested making little discs of beta alumina, no one questioned him. He said he was considering using the discs as a battery electrolyte. He then planned to combine the electrolyte with sodium and sulfur and create a battery cell. There was no denying that the idea was different. Batteries of the day used liquid electrolytes—mostly aqueous solutions. They did not use glass or any other solids. But this was Joe Kummer, so one of his colleagues, Matthew Dzieciuch, took it to heart. Dzieciuch went back to his office and laid plans to synthesize a little piece of glass made from beta alumina. Dzieciuch, who had come to Ford only a year earlier after earning his PhD in electrochemistry at the University of Ottawa in Canada, knew the material. It was similar to the liners used in the glass furnaces at Ford's mighty River Rouge plant. It didn't sound like a terribly complex task.

Nor was it a high-priority project for Dzieciuch. His main interest was fuel cells. But this was one of the beauties of working at Ford Research. Henry Ford II had made the facility a high priority and wanted it modeled after Bell Telephone Laboratories, where the first electronic transistor had been developed. At Ford Research, like Bell Labs, the scientists had tremendous personal freedom. They could pursue almost any idea that piqued their curiosity, which was why Dzieciuch now had the latitude to fashion a few small discs of beta alumina.

In his spare time, Dzieciuch took some aluminum oxide and mixed it with sodium carbonate. Heating it in a furnace, he produced a fine white powder. X-rays proved it was beta alumina. He pressed it in a die, sintered it, and found, to his great delight, that he now had several dime-sized discs made of beta alumina.

To anyone else, it would have looked inconsequential. But Dzieciuch was proud of his little glass discs. So was Kummer. "Joe was so happy," Dzieciuch recalled

Ford scientists Neill Weber (*left*, holding test tube battery) and Joe Kummer invented and patented the sodium–sulfur chemistry. Their battery, which used a solid electrolyte, launched the era of fast ion transport. (PHOTO COURTESY OF FORDIMAGES.COM.)

decades later. “He said, ‘Can I have a couple of those?’” Together, the two scientists took a disc to the lab’s glass blower, who formed a test tube around it. It was the beginning of a new kind of battery.

No one was sure exactly how far Joe Kummer planned to take this “battery”—whether he saw it as an actual product or just as a science experiment. Kummer had talked about fast ion transport. He wanted to see if sodium ions could travel through the tiny voids in the beta alumina. Later, he would ask another scientist, Ron Radzilowski, to measure sodium conductivity in the beta alumina. Radzilowski did and returned with the news that beta alumina was highly conductive. Kummer and Weber subsequently applied for a patent. Still, their long-term intentions remained unclear.

Years later, Dzieciuch readily admitted he had no idea if Kummer’s battery concept would work. But at the time, he thought it was worth pursuing. “I was young,” he said years later. “I guess I didn’t know any better.”

The first thing Stan Whittingham noticed was the sunshine. In Palo Alto, you could look up in the morning and see a bright blue sky. The days and nights were mild, the skies were often cloudless, and there was never any snow. The campus of his new employer, Stanford University, was a product of that climate. It had a great, green, grassy quadrangle surrounded by palm trees and bright yellow sandstone buildings with red tile roofs. California mission architecture, it was called.

It was a far cry from the University of Oxford in England, where Whittingham had recently earned his PhD in chemistry. Oxford was one of the world's most prestigious universities, and its campus was at least 700 years older than Stanford's. Teachings from Oxford could actually be traced back to 1096—about 468 years before the birth of William Shakespeare. The vaulted ceilings, pointed arches, buttresses, and spires stood in stark contrast to Stanford's mission architecture. And then there was the weather—great gray stretches of clouds that could go on for days, maybe weeks.

"The choice was, do I go to California and see some sunshine or do I stay in the UK and get an industry job?" Whittingham later recalled. "I chose the sunshine."

Then, of course, there was the job itself. Whittingham arrived at Stanford in 1968 as a twenty-seven-year-old postdoc—a temporary academic position that prepares a newly minted PhD for a career in research or academia. Oxford had proven to be the ideal place to launch such a career. Whereas most university chemistry departments were biased toward industry, Oxford's was more deliberately theoretical. It created a foundation for someone who wanted to do advanced scientific research, write peer-reviewed papers, and maybe even make a breakthrough or two—which is exactly what Whittingham hoped to do at Stanford.

He wasn't the first Oxford chemistry graduate to make the trek to Stanford. His advisor at Oxford, Professor Peter G. Dickens, had sent an Oxford student there only three years earlier. And the feedback was good. The Stanford area, he said, was a wonderful place to live and work.

Whittingham quickly fit right in at Stanford. He could have been a movie prototype for a 1960s scientist. Trim and clean-shaven with neatly combed dark hair and conservative horn-rimmed glasses, he looked a little like an academic version of the 1950s American movie star Gregory Peck. He started his work under a Stanford materials science professor named Bob Huggins. Huggins was just forty years old at the time but was already known and respected halfway around the world in Oxford. He had earned his doctorate in metallurgy at the Massachusetts Institute of Technology (MIT) only fourteen years earlier. With just a little more than a decade between them, Huggins was almost like a contemporary of Whittingham, albeit a more experienced contemporary.

In the year before Whittingham's arrival, Huggins had become increasingly interested in some work being done at the Ford Motor Company. There, researchers had created something called a sodium–sulfur battery using an electrolyte called beta alumina. In 1966, two of the researchers, Joseph Kummer and Neill Weber, had applied for a patent[3] on the battery, and it was beginning to create quite a little stir within the electrochemistry community.

During the course of everyday work, Huggins would often have lunch with his grad students and postdocs at the school's Tresidder Memorial Union, or at a restaurant called Round Table Pizza on University Avenue in Palo Alto. There, he occasionally discussed his thoughts about Ford's new battery technology. Sodium–sulfur was fundamentally different than the batteries that the world had come to know, he said. Most batteries had three main parts: two metal terminals—a negative pole (or electrode) called an anode and a positive pole (or electrode) called a cathode—and a liquid electrolyte. To put it more simply, a conventional battery was two hunks of metal separated by an aqueous solution. But the Ford battery was exactly the opposite. It had a hot liquid anode and a hot liquid cathode separated by a *solid* electrolyte. The electrolyte was essentially a ceramic with miniscule channels that allowed ions—electrically charged molecules or atoms—to shuttle back and forth through it, between the battery's anode and cathode.

It was a bit of a head-scratcher for much of the scientific community. Batteries just weren't made that way. But Ford was bullish on the new technology, and the media buzz around it was growing. In 1966, the automaker's president, Arjay Miller, had called a press conference to announce that Ford was already working on a car to be powered by a secret new power source. "The ideal answer would be the development of a vehicle power source that would not produce emissions," Miller told the *New York Times* in September 1966.[4] "The most promising candidate at present appears to be a battery-powered electric car."

For the technical community the announcement was a stunner. Big auto companies were always working on dozens of long-range research projects in their labs, but they seldom had their company presidents convene press conferences to promote them. Curiosity around the project naturally grew as competitors and media wondered about the secret new power source.

Within a few weeks, though, word had trickled out: Ford's secret power source was called the sodium–sulfur battery.[5] By mid-1967 the company had told the *New York Times* that it expected to have a working sodium–sulfur battery ready in 1970, and an electric production vehicle on the road approximately eight years after that. "We're convinced this is the real answer," said Jack Goldman, director of Ford's research laboratory.[6]

Huggins followed the evolving Ford story, but not because he was interested in electric cars or even batteries, per se. No, Huggins's interest was much more fundamental than that. Being a metallurgist, he wanted to know more about the mechanisms that allowed ions to shuttle back and forth through Ford's solid electrolyte. In essence, the battery's sodium ions were tunneling through a crystal lattice made from a material called beta alumina. The phenomenon was known as "fast ion transport." *That* was what interested Huggins.

Huggins viewed fast ion transport as a potential area of study for his staff. Typically, Huggins had anywhere from four to six grad students working for him, along with one or two postdocs, in a little three-room lab. They were all bright. Stanford was, after all, one of the finest research universities in the world. But he had one postdoc who seemed ideal for the task, and that was Stan Whittingham.

In retrospect, it would later appear as if Whittingham's life had been a series of assigned activities leading up to that moment—a destiny of sorts. Born Michael Stanley Whittingham in 1941 near Nottingham, England, he was the oldest child of a father who was a civil engineer and a mother was who was a chemical technician. As an infant during the early years of World War II, his family had led a nomadic life by necessity. Every time German aircraft would roar over an English town and bomb the local airstrips, his father would pack up the family and gather construction crews for the rebuilding effort. As a result, the Whittingham family was continually changing its residence. "I was very much mobile in those years," Whittingham recalled decades later. "I don't think we stayed anywhere for more than a few months."

When the war ended, the family settled into the town of Stamford in Lincolnshire, about ninety miles north of London. Stamford was a small town—less than twenty thousand people—but its history went back more than a thousand years. It also had a prestigious school, the Stamford School, which dated back to 1532. Stamford School was known for the beauty of its Gothic architecture, as well as its distinguished alumni, which included politicians, judges, authors, playwrights, clergymen, athletes, and countless academics. It was a public educational institution that would admit students who appeared to show academic promise, and then would pay their tuition.

Stan Whittingham was one such student. He'd shown enough promise to be admitted at a very young age, and then had stayed in the school until he was eighteen. Almost from the beginning, he'd been "A-streamed" into a group of high achievers in math and science. By the end of high school, he'd taken two to three years each of chemistry, physics, and math, including two years of college calculus and differential equations. The school fired his imagination, Whittingham said, because its teachers emphasized lab work over book learning. For Whittingham, life in the lab was inspiring. And he was good at it.

Whittingham's subsequent admission into the University of Oxford, while not exactly pro forma, was not in doubt for very long. His only weakness was in Latin, and he needed tutoring from Stamford's headmaster to ensure that he would pass Oxford's Latin exam. Once that was done, his path to admission was clear. Although Oxford was a prestigious university that turned away close to 80 percent of its applicants, it recognized the value of an education at the Stamford School and was unlikely to reject one of Stamford's top science students. Whittingham was virtually a perfect fit for Oxford's renowned chemistry program.

At Oxford, Whittingham earned his bachelor's degree in three years, then moved directly on to graduate school. His PhD work set the stage for later efforts. In his thesis, he described the behavior of tungsten bronze—a shiny metallic alloy that allowed for fast movement of potassium, sodium, and lithium ions.

It was pretty close to a perfect background for his new task at Stanford. At this point, he had somehow found the time to meet his wife-to-be, Georgina, who was studying for her master's degree in Spanish at Stanford. The two married in 1969 and moved into student housing. About eighteen months after that—and after the birth of their first child—they moved to a little two-bedroom home in Palo Alto.

They rented at first, but their landlady eventually offered to sell it to them for about $30,000, so they scraped together the money and bought it.

In 1970, when the couple made the purchase, it was possible for a postdoc with a $15,000-a-year salary like Whittingham's to afford a house in Palo Alto, largely because the Silicon Valley hadn't yet left its mark on real estate prices. At the time, the area's home values were just beginning to rise. Apricot, pear, and plum orchards were still among the area's main local businesses.

By that time, Whittingham's responsibilities at the lab were also growing. Huggins had temporarily left Stanford for a post in Washington, DC, where he was in charge of research programs at the Department of Defense's Advanced Research Projects Agency (DARPA). While he was gone, he left the fast-ion research in the capable hands of Whittingham—a blessing, as it turned out, for Whittingham's career, although it may not have felt like it at the time.

In the absence of Huggins, Whittingham's job was to describe what was going on inside Ford's beta alumina electrolyte—in particular, to figure out how fast the sodium ions were moving through it. This, as it turned out, was a key moment in battery history, because the battery community was beginning to wake up to the fact that ions could move fast through solids. To be sure, those aware of this phenomenon were a small group, but they suspected they were onto something big.

Thus, Whittingham's task was to determine how fast the sodium ions were moving through the glass electrolyte in Ford's battery. This, however, was no simple task. To do it, Whittingham needed to have two reversible electrodes—that is, electrodes that would allow ions to shuttle back and forth—on each side of the beta alumina electrolyte. But the ionic conductivity of beta alumina was so great that it couldn't be readily measured with the traditional metal electrodes of the day, which were often platinum. So Whittingham had an idea, and he built a makeshift battery to carry it out. For the battery's electrodes, he used tungsten oxides, which he already understood intimately from his days at Oxford. Then he placed Ford's beta alumina in between them as an electrolyte. When he applied a voltage to one end of the apparatus, he could measure the electrical current at the other side. From there, he could work backward and calculate the diffusion of ions across the beta alumina. It was complex work, but Whittingham was already familiar with the science from his days at Oxford.

In this way, Whittingham was able to measure the speed of the ion transport through the beta alumina. The sodium ions would start at one tungsten oxide electrode, shuttle through the solid electrolyte, then insert themselves in the other tungsten oxide electrode. There, they would *extract* themselves, shuttle back through the electrolyte again, and stop at the other electrode. And it all happened at high speed. This was, after all, *fast* ion transport.

Therein lay two unexplainable scientific phenomena. First, ions weren't supposed to travel through solids this fast. Second, scientists were at a loss to explain how ions could insert and extract themselves so quickly from the electrodes. "If you looked at the literature of the time, battery chemists didn't really understand what was going on," Whittingham said many years later.

The surprise in all of this was that Whittingham hadn't merely identified fast ion transport in beta alumina; he had actually built a solid-state battery (a battery with a solid electrolyte). As he pumped sodium ions back and forth, he learned a lesson that was previously unknown, even to the best battery scientists of the day. His shiny tungsten oxide electrodes became *sodium* tungsten oxide electrodes. They were changing—capturing the sodium ions between the thin layers—and being transformed into a new chemical compound.

The technical term for the process was *intercalation* (pronounced "in-TURK-a-lay-shun"). During intercalation, an ion inserted itself in between atomic structures of a material, actually changing the material's chemical composition. Then, in a reversal process, the ion *un*-inserted itself, leaving behind no damage.

There was actually nothing new about intercalation itself. In truth, it wasn't even a chemistry term, having been eased into science after being borrowed from the Gregorian calendar. The *Oxford English Dictionary* (ironically) referred to it as "a day inserted into the calendar," as in the case of the fourth-year insertion and removal of February 29 in the 365-day year. In other words, February 29 was intercalated into the calendar every four years. In that sense, the term was apt for the chemistry community because it wasn't just about the insertion but about the extraction as well.

No one, however, had ever discussed intercalation in reference to batteries. "None of the batteries of that time operated by intercalation mechanisms," Huggins said decades later. "This was something altogether new."

By 1971, when Huggins returned to Stanford from his stint in Washington, he began working with Whittingham to tell the electrochemical community what they had discovered. Together, the two published a litany of papers in technical journals like the *Journal of the Electrochemical Society*,[7] *Solid State Chemistry*,[8] the *Journal of Chemical Physics*,[9] and the *Journal of Solid State Chemistry*.[10]

The papers would have had little historical impact, however, were it not for one that employed one of the most prophetic titles in the history of scientific literature. On October 18, 1971, at a National Bureau of Standards meeting in Gaithersburg, Maryland, Whittingham and Huggins delivered a paper titled "Beta Alumina—Prelude to a Revolution in Solid State Electrochemistry." The paper's title was extraordinary, not only because it accurately predicted a major transformation to come in electrochemistry but because it dared to use the term "revolution." In the world of scientific publishing, terminology tended to be precise and dry. But that unemotional and precise style was, to be sure, deliberate. In scientific publishing there were few real sins, but one was to be commercial and another was to appear to be self-promotional. In that sense, words like "groundbreaking," "radical," or "revolutionary" were to be avoided. Yet here, Whittingham and Huggins were suggesting that their research pointed to a coming change that was nothing short of a scientific revolution. And they weren't burying the language back in the conclusion on page 6. They were putting it right up front, in the title, for everyone to see. "Bob and I discussed it and we really believed that this whole idea of fast ion transport was going to revolutionize electrochemistry, which had always been an aqueous field," Whittingham said. "We believed all the materials scientists were going to rush into it."

Indeed, Whittingham and Huggins had a hunch that something big was going on, maybe even bigger than the researchers at Ford had realized. It wasn't simply a matter of one company producing a sodium–sulfur battery. It was more fundamental than that, and breathtakingly more important.

It didn't take long before others in the community started seriously considering the science behind Ford's solid-state battery. In September 1972, a few dozen scientists attended a conference in Belgirate, Italy, called Fast Ion Transport in Solids. The meeting included one week of educational courses, followed by a weeklong technical conference. It was there that the topic of solid-state ionics began to get traction and the idea of intercalation compounds was examined more seriously. "At that point, we started discussing whether we could build batteries with fast ion transport in the electrodes," Whittingham said.

Thus, two new topics were now on the table: first, a battery with a solid electrolyte, like Ford's beta alumina; second, a battery with a liquid electrolyte, combined with intercalation compounds in the electrodes. To be sure, the ideas were still very new and primitive. No commercial products were being considered yet. The discussion was about the underlying science. Still, there was no denying that the possibility of a new type of battery loomed on the distant horizon.

Beyond a few select groups within the materials science community, however, there was little talk of the new concepts. But at Stanford, there were now two separate teams examining fast ion transport. There was also a third team at AT&T Bell Labs in New Jersey, and a fourth at Imperial College in London. But that was about it.

No one in the consumer press picked up the story, of course, despite Whittingham's use of the term "revolution." It was far too early for that. Newspaper reporters wrote about revolutions, but not about revolutions in solid-state ionics. Thus, awareness of the new science was extremely limited. Even in the battery community, only a handful of people knew about the revolution in fast ion transport.

Besides, by 1972, the Ford sodium–sulfur narrative was already starting to lose some of its luster. Ford still hadn't placed its sodium–sulfur in a test vehicle, in part because of the growing internal knowledge that the battery needed to be heated to about five hundred degrees Fahrenheit to work properly. There were increasing concerns over the potential for fire, and Ford executives frowned on the idea of letting an experimental electric car roll down the streets of Dearborn like a flaming chariot.

Thus, the tale of the fast ion transport revolution never made it very far past the attendees of the conference in Belgirate. Still, Whittingham and Huggins continued to believe. They saw a revolution on the horizon, and nothing was about to change their view of that.

When Whittingham and Huggins presented their paper in October 1971, there was, of course, nothing new about batteries. Virtually every consumer knew that batteries could be purchased at the local grocery store for use in toys, flashlights, and transistor radios and that batteries started their car's engine every morning.

For the most part, though, batteries were taken for granted in 1971. That was because the technology had been relatively static for more than a century, and as such had been relegated to a rather low rung on the technological ladder. Rockets, televisions, and computers were much more compelling topics, especially for the national press.

At one time, however, the battery had been big news. It had started as a curiosity, a solution to a scientific debate that had raged for nearly eight years. Alessandro Volta, a professor of experimental physics at the University of Pavia in Italy, first demonstrated the technology in 1800, not as a means of energy storage but as a way of winning a long-running dispute with an Italian physician named Luigi Galvani.

The debate, oddly enough, centered on frog legs. Years earlier, Galvani had noticed a strange phenomenon: When he touched the severed leg of a dissected frog with his scalpel, the leg twitched. He concluded that the twitching was the result of electricity accumulated in the leg muscle—electrical fluid, he called it. In 1791, Galvani published a technical paper, "De viribus electricitatis in motu musculari commentarius"[11] (Commentary on the Effect of Electricity on Muscular Motion), explaining his conclusion.

Ever the scientist, however, Volta was suspicious of the physician's theory. He believed that the twitching was the product of electrical current passing between two dissimilar metals. The current, he reasoned, traveled from the scalpel, through the frog leg, and into a metal plate below.

The debate, which sounds dry today, stirred an amazing amount of controversy at the time. Scientists throughout Europe began lining up on both sides of the issue, even publishing papers to explain their positions.

Volta was certain of his theory. As proof, he placed different types of metals in his mouth and believed he felt the strange tingle of electrical current running across his tongue.

In March of 1800, two years after Galvani's death, Volta proved his point through the construction of something he called the voltaic pile. The pile consisted of chunks of metal and cardboard—a circular piece of zinc, a silver half crown coin, and a slice of cardboard soaked in saline water. Atop those were another piece of zinc, another coin, another piece of wet cardboard, and so on. Hence the name "pile."

Simple as it was, the voltaic pile proved Volta's point. If a man wet his hands and touched the top and bottom of the stack, he received a considerable shock. In essence, the electrical current traveled from the silver, through the wet cardboard, to the zinc. No frog legs were needed.

The discovery proved Volta's point and made him a celebrity in his day. He toured Europe, demonstrating his voltaic pile. Napoleon Bonaparte, a self-proclaimed science buff, even granted Volta an audience, later making him a count.

Almost lost in the debate, however, was the fact that Count Volta had essentially built a battery. In a letter to Sir Joseph Banks of England's Royal Society in 1800, Volta seemed only mildly aware of the implications of his pile. He did, however, write that the "apparatus" would have "an inexhaustible charge, a perpetual action or impulse of electrical fluid."[12] Therein lay the invention. Volta's use of the word "inexhaustible," while not technically precise, described the difference between his voltaic pile and anything that had preceded it.

Electrical storage was the key difference. Scientists had known about various forms of electricity for centuries. The Greek philosopher Thales of Miletus had toyed with the concept of static electricity as far back as 600 BCE. And Ben Franklin had felt a jolt of electricity when he famously flew a kite in a thunderstorm in 1751. But controlled storage of electricity was trickier. Scientists of the day knew that electricity could be held in water in glass jars and then conducted in and out with metal wires or nails.[13] Known as Leyden jars, the devices could capture enough electricity to deliver a real electrical wallop, and thus became an odd form of pre-television parlor entertainment.

But Volta's pile was critically different than the old Leyden jar. Whereas the jar delivered its big bang all at once, the pile produced a steady flow, a river of electricity. For the first time, electricity became available for periods of time instead of single instants. Volta had created a silver–zinc battery.

Real awareness of the value of electrical storage took a few more years, but scientists gradually began finding uses for it. About thirty years later, an English scientist named Michael Faraday developed electric motors and generators, setting the stage for the delivery of mechanical power with electricity. With Volta's battery and Faraday's electric motors, it was now possible to drive a set of wheels.

At this point, the battery became inextricably linked with transportation, whether the world knew it or not. And it would forever remain that way. Suddenly, the idea of a battery-driven carriage was in the air. In Hungary in 1828, a Benedictine priest named Ányos Jedlik constructed a crude model of an electrically powered carriage;[14] in Vermont in 1834, a blacksmith named Thomas Davenport built a full-scale electric horseless carriage;[15] in the Netherlands in 1835, a professor named Sibrandus Stratingh created a small-scale electric car with a non-rechargeable battery; and in Scotland, an inventor named Robert Anderson fashioned a crude horseless carriage with a non-rechargeable battery sometime between 1832 and 1839.[16]

In a very primitive sense, the electric vehicle had arrived. None of those early carriages succeeded commercially, of course, for many reasons. Their use of non-rechargeable batteries meant that the batteries would have to be repeatedly replaced when depleted, which was expensive and inconvenient. Moreover, there was no manufacturing to speak of, and the road conditions of the day were too poor for powered vehicles. But within fifty years, the stage was set for greater success. In 1884, English inventor Thomas Parker built the first manufacturable electric car;[17] and in the US in 1887, William Morrison, a chemist with a keen interest in batteries, began building electric carriages in a factory in Des Moines, Iowa. Morrison built only twelve but is said to have received sixteen thousand requests for information.

By 1900 the future was starting to look bright for battery-powered vehicles. More than thirty-three thousand electric cars were driving on US roads, accounting for about 38 percent of the total number of vehicles in the country.[18] And for good reason. Electric cars offered advantages over gasoline-burning cars. They were quieter, smelled better, and were easier to start. They required no hand cranking, and women especially preferred them. Still, there was a chronic issue—the battery. The driving range was too short and recharge time, too long.

That's where Thomas Edison came in. Edison looked at the rising popularity of the automobile and decided that battery-powered cars were the way to go. In retrospect, it was a surprising conclusion, since Edison had long been skeptical about the commercial prospects for rechargeable batteries. After investigating them intensely in the early 1880s, he had concluded that they were "a catch-penny, a sensation, a mechanism for swindling by stock companies." And most American electrical engineers agreed with him.[19]

By 1899, however, Edison was ready to go back to work on rechargeable batteries. To be sure, he didn't plan to enter the auto manufacturing business. There were already plenty of companies building electric cars, including Pope Motor Car Company, Baker Motor Vehicle Company, Woods Motor Vehicle Company, and the Electric Vehicle Company. No, Edison wanted only to build a better battery, because he saw a need for electric cars. "Electricity is the thing," he said. "There are no whirring and grinding gears with their numerous levers to confuse. There is not that almost terrifying uncertain throb and whir of the powerful combustion engine. There is no water circulating system to get out of order—no dangerous and evil-smelling gasoline and no noise."[20]

Today, it's almost impossible to overstate the legitimacy that the name Edison conferred upon the electric car. By 1899, when he returned to his battery development efforts, Edison was known worldwide. Newspapermen reported his every public statement and eagerly awaited his next patent. And by the beginning of 1899, Edison had already accumulated 754 US patents[21] (on his way to a total of 1,093). By the time he finished his career, Edison would have 424 patents in electric light and power, 199 in phonographs and sound recording (despite his own hearing loss), 186 in telegraphy and telephony, 147 in batteries, 53 in mining and ore drilling, and 49 in cement.

Moreover, the diversity of his patents was breathtaking. He invented talking dolls, miners' safety hats, night telescopes, electric meters, universal stock tickers, tornado-proof houses, and electric dynamos. He also invented an electrographic vote recorder, a rotor-lift flying machine, a device that addressed mail, an electric cigar lighter, a sap extractor, an electric pen, a dictating machine, a radiotelephone receiver, an acoustic clock, a violin amplifier, moving pictures with sound and color, and, of course, the phonograph,[22] among hundreds of other devices. And although he did not invent the light bulb (as is often suggested), he did alter the way the light bulb was constructed, giving it a far longer life. Moreover, almost by pure force of will, he designed, manufactured, powered, and built the world's first incandescent electric lighting system.[23] By 1899, he was a fifty-one-year-old living legend, known for having overcome his lack of formal education with an extraordinary commitment to intense study and labor, sometimes working for fifty-four hours at a stretch without rest.[24] It had reached the point where businesses tried to gain legitimacy through any kind of remote linkage to his name. Therefore, to have him step forward and promote the electric car was, well . . . akin to having God Himself come out in its favor.

Still, Edison found the development of a better battery unlike anything he had taken on previously. On the surface, his goal sounded simple—he wanted to create a battery that offered more utility than the lead–acid unit that had existed already for forty years. Lead–acid, invented by French physicist Gaston Planté in 1859, had obvious advantages. It could be recharged, didn't corrode, and was relatively inexpensive. But lead was also dense and heavy. As a result, its energy density (the amount of energy it stored per unit weight) was low. A lead–acid battery offered between eight and thirteen watt-hours per kilogram of mass—a range that was unimpressive for anyone who wanted to power a car for any distance.

Thus, Edison was determined. He wanted to build an automotive battery that was cheap and light. But from the outset, he encountered difficulties. Edison started in 1899 by trying to develop a rechargeable zinc–copper battery, but soon abandoned it for a variety of reasons, including weight. He then moved to cadmium–copper, filing for patents in 1900. But cadmium, too, had its drawbacks—namely, cost—so he left that behind as well.

When he again changed his preference in 1901, Edison became convinced he had found the right materials: an iron anode (the negative pole) and nickel cathode (positive pole). He brought together a group of investors to bankroll the development and manufacturing efforts. Then he had his former assistant, Dr. Arthur Kennelly, deliver a paper on the battery to the American Institute of Electrical Engineers in May of 1901. The paper, titled "The New Edison Storage Battery,"[25] described vast improvements over lead–acid and zinc-based batteries. Kennelly told a slightly skeptical audience in New York that Edison's nickel–iron battery would get nearly three times the energy density (about thirty-one watt-hours per kilogram) of lead–acid, would be charged in as little as one to three hours, would not deteriorate substantially during use, and would be inexpensive.

Edison used the press to pump up public interest in his new firm, which he called the Edison Storage Battery Company. He planned a publicity campaign that focused on rigorous road tests—driving over poor roads and dropping batteries out of second- and third-floor windows. He told reporters, "These batteries will run for a hundred miles or more without recharging. They can be charged in a few hours." And, he said, "I do not know how long it would take to wear out one of the batteries, for we have not yet been able to exhaust the possibilities of one of them. But I feel sure that one will last longer than four or five automobiles." By July, Edison was claiming that he had reached the summit, the "final perfection of the storage battery," marking the new advent of the electric automobile.[26]

Unfortunately, the reality didn't match the hype. The nickel–iron battery reached the market in 1903 with two serious defects: It leaked and, worse, it lost capacity for unknown reasons. Edison attacked the problems in typical Edisonian fashion, hiring a group of "eighteen men and boys"[27] to work day and night in his labs to search for solutions. After some time, he developed a "spongy composite of nickel and cobalt"[28] that he thought solved the cathode problems. In July 1905 he again declared complete success.

But he was wrong again. It turned out that large volumes of cobalt were not readily available and Edison had to switch the material one more time. He went from the nickel cobalt cathode to a material he called nickel flake. Nickel flake, he said, would solve all the problems. Unfortunately, Edison needed new manufacturing equipment to produce the nickel flake cathodes . His new manufacturing target date, which had originally been 1908, slipped back to 1910. Still, he began building batteries for use in streetcars, submarines, and railcars.

At this point, however, investors began to rebel. Edison's promise of an automotive revolution wasn't happening. A letter from one investor suggested his colleagues were growing "very ugly" and were talking about a lawsuit.[29] Edison quieted the investors, but by this time, too many years had passed. Battery competitors were already gobbling up a substantial piece of the electric car market, and gasoline cars were getting better, making the economics of his venture look even shakier.

To combat the growing problems, Edison turned to one of his favorite tactics: the press (a tactic that would again be favored by battery and auto companies a century later). In November 1911, he told the *New York Times* that his battery was ready to spark a revolution in automotive transportation. The *Times* dutifully responded with a gushing article describing the battery as "simple, light, easy to take care of, and far more efficient than the old lead battery." It concluded by quoting a supportive engineer who said, "This invention alone is enough to put electrical transportation on a sound and successful basis."[30]

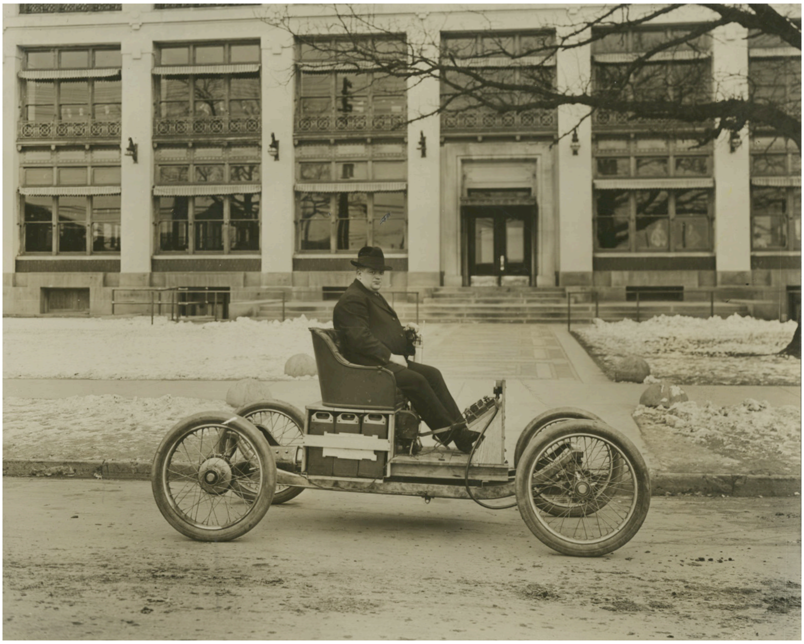
Except that it wasn't. By 1912, the news had gotten even worse for Edison. Charles F. Kettering, founder of Dayton Engineering Laboratories (later to be known as Delco), developed a self-starter for gasoline automobiles. Kettering, an enormously practical man, took a small motor that he had previously invented for the National Cash Register Company and adapted it to automobiles to serve as the self-starter. The impact was almost immediate. The automated self-starter was a huge step forward, essentially eliminating the hand crank, which was one of the widely recognized drawbacks of the gasoline engine. With the self-starter, which got its start at Cadillac, the gasoline engine looked infinitely more appealing.

As prospects for his battery revolution grew dimmer, Edison changed his approach. Sometime in 1913, he began talking with Henry Ford about the nickel–iron battery and the electric car. It was inspired strategy. Ford, one of the crustiest and most eccentric of all turn-of-the-century manufacturing mavens, had an uncharacteristic soft spot for Edison. In the book *Friends, Families & Forays: Scenes from the Life and Times of Henry Ford*,[31] author Ford R. Bryan (a Ford family member) actually described Ford's feeling as a "respect for Edison that approached adoration." Moreover, Ford had a grudging respect for the electric car. In 1913 he bought a Detroit Electric, an electric vehicle built by the Anderson Carriage Company, for his wife, Clara. Like many wealthy executive wives of the day, Clara preferred the clean, quiet electric car to the noisy, dirty gasoline engine. She used her Detroit Electric to drive from Detroit to the family's farm in Dearborn on a regular basis. When it became apparent that the drive to and from Dearborn came precariously close to the limits of the battery, Ford had a charger installed for her at the farm. Still, as of 1913 Henry Ford had expressed no public interest in building and selling an electric car.

Little is known about how Edison changed Ford's mind. But in 1914 Henry Ford did a sudden reversal. On January 11, the *New York Times* reported that Ford planned to begin manufacturing an electric automobile within a year. After first describing Edison as "the greatest man in the world," Ford told the *Times*, "Mr. Edison and I have been working for some years on an electric automobile which would be cheap and practicable. Cars have been built for experimental purposes, and we are satisfied now that the way is clear to success. The problem so far has been to build a storage battery of light weight which would operate for long distances without recharging. Mr. Edison has been experimenting with such a battery for some time."[32]

The seriousness of Ford's plan is, to this day, unknown. But he did offer details, telling the *Times* that he intended to use a 405-pound nickel–iron battery. He also indicated that the entire car would weigh 1,100 pounds, would run for one hundred miles before needing a recharge, and would cost $600 (comparable to about $15,500 in 2022). Internally, he told colleagues that the electric car would be built in a new Detroit factory managed by his twenty-one-year-old son, Edsel.

But Ford Motor Company built only two prototype electric cars. The first, completed in late 1913, consisted of an open frame and a single seat big enough for two people. In pictures, the car's 400-pound battery fit inside a treasure-chest-like box under the seat. The vehicle had no steering wheel, just a tiller to allow for turning. A second prototype vehicle turned up in June 1914. Slightly more advanced than



Though it is not well known, Thomas Edison and Henry Ford collaborated on an electric car in 1913. The car's nickel–iron battery weighed approximately four hundred pounds and resided under the seat. Pictured here is Ford chief engineer Fred Allison. (PHOTO FROM THE COLLECTIONS OF THE HENRY FORD [84.1.1660.865/THF132273].)

the first, it was built on an open Model T chassis. It included a steering wheel and contained two sets of nickel–iron batteries. The vehicle weighed 1,350 pounds and featured a cruising speed of seven miles per hour.

That car, however, would be the final prototype electric vehicle built by Henry Ford. Testing it on Michigan roads, Ford engineers learned that Edison's batteries weren't particularly good at handling cold weather. Ford's secretary, Ernest Liebold, who was in charge of the project, reported in 1914 that "the internal resistance of the batteries was very high and increasingly so during extremely cold weather. It offered a problem in what we were going to do in wintertime with this difficulty in not being able to get sufficient voltage, how we were going to operate the starting motors."[33]

The cold weather performance may have been the final nail in the coffin of the Ford–Edison electric car. Liebold is said to have responded to dozens of inquiries about the car, replying only that plans had changed. He never publicly admitted that the project was actually dead.

Edison, meanwhile, resigned himself to the fact that the nickel–iron battery would not displace the internal combustion engine. Ironically, it was Ford's low-cost Model T that stood in the way of it, along with Kettering's self-starter. Edison would subsequently attempt to design and manufacture a truck for use with his battery, but he eventually gave up on that, too.

Ultimately, Edison would find other applications for his nickel–iron battery—railroad signals, switches, submarines, miner's lamps, ship lighting, ship radios, and backup power for industrial applications.[34] But fifteen years into the project, the reality loomed large: Even for Thomas Edison, the battery-powered car had just been too great a challenge.

The auto industry would go another half century before it would again dare to think about an electric car. And by the time it did, the public considered it a new idea.

The impetus for the electric car's return was air pollution. By the early 1960s there was plenty of evidence to suggest that gasoline-burning vehicles were leaving behind a toxic combination of carbon monoxide, hydrocarbons, sulfur oxides, and nitrogen oxides in the air. In big cities like Los Angeles there was visible proof of the problem, captured convincingly in photos of the city's smog-choked downtown. About that time, the US Congress passed the Clean Air Act of 1963 and the country began to look for solutions. It didn't take long before alternatives to gasoline were being discussed, and the electric car emerged anew again.

Ford Motor Company was among the first of the big-name companies to reconsider the electric car, applying for a patent on its sodium–sulfur battery on October 22, 1965. But Ford was by no means alone. In 1966, General Motors added itself to the electrification discussion by showing off a prototype vehicle called the Electrovair.[35] The Electrovair was essentially a Corvair that took a page from Alessandro Volta's work, using silver–zinc batteries for power. It was about eight hundred pounds heavier than the gas-burning Corvair but could hit a top speed of eighty miles per hour, which seemed to impress GM engineers. Unfortunately, it could only be recharged about a hundred times before the battery died.

By this time the media had started ratcheting up the intensity of the pollution story. In January 1967, *Time* magazine published a cover story called "Menace in the Skies,"[36] detailing the sad state of air pollution in America's biggest cities. The story came complete with a cover shot of the Los Angeles downtown blanketed by smog so thick that the city's buildings were barely visible. If the public hadn't been aware of the problem up until that point, it was now.

Around the same time, American Motors Corporation (AMC) and battery maker Gulton Industries teamed to produce a three-seat electric vehicle that measured just seven feet long.[37] AMC made the dubious claim that the car could travel 150 miles at 50 miles per hour using lithium nickel fluoride batteries. Still, the project quietly disappeared.

Meanwhile, in Japan, Mitsubishi Heavy Industries teamed with the Tokyo Electric Power Company to build an electric car.[38] And British Motor Holdings, the UK's largest auto producer, started building an electric car powered by a zinc–air battery.[39] Even Westinghouse Electric Corporation got in on the act, announcing in 1968 that it was putting together a short-range electric vehicle called the Markette, which would use eight hundred pounds of batteries.[40]

But for everyone involved, the venture into electric vehicles quickly became daunting. Energy density of the batteries was low, cost was high, performance was poor. The easiest way around it was simply to tell reporters that the vehicles would reach production at some vague point in the future. Japanese manufacturers said they expected electric cars in five to ten years;[41] Ford said ten years;[42] the *Chicago Tribune* reported that a wide variety of new electric cars would be tooling down the streets in five years.[43] And at the University of Pennsylvania, a professor of mechanical engineering even offered an explanation for the five- to ten-year theory, saying that it was a product of the speedy evolution of technology. "If you look back ten years, you are just a year short of Sputnik," he told the *New York Times*. "Look what has happened to technology in that time. I think in the future we will not only have electric cars but electrified highways and even programmed driving. You'll hop into the car, set it, and it will do the rest."[44] The professor was probably about seventy years ahead of his time. The ten-year figure was wildly unrealistic, probably inspired by . . . well, nothing really, other than it seemed like a nice, round number.

Still, the public bought into it. In 1970, a survey by the electric power industry indicated that "the youth market is even more eager than the over-sixty set for a short range, limited-speed electric car costing $2,000 or less."[45]

The only thing standing in the way, it seemed, was reality. Automakers *wanted* to find an innovative solution, but they found battery technology to be more maddeningly complex than they had ever anticipated. Chemistries like silver–zinc, zinc–air, lithium nickel fluoride, and sodium–sulfur always looked good initially. But then the engineers invariably ran into some impenetrable roadblock. In a few companies, such as Westinghouse, engineers threw up their hands and halted development.[46] Others, like Ford, GM, and AMC, stayed with it, rummaging through the periodic table in search of some new combination of materials, some kind of breakthrough.

No project demonstrated the technical quagmire better than GM's Electrovair. The Electrovair, the company's engineers said, had looked great until they started building vehicles. But they soon concluded that the Electrovair would cost about $15,000—"the price of a couple of Cadillacs."[47] Therefore, the powers that be at GM began to question it. It was a steep price for a vehicle that offered such limited utility. Eventually, talk of it simply evaporated.

"We found there is a big difference," GM project engineer Dr. Craig Marks told the *New York Times*, "between talking about electric cars in paper studies and actually building one."[48]

By 1972, some of the postdocs and grad students in Bob Huggins's lab at Stanford were beginning to get job offers from industry. The best offers tended to come from the East Coast. Back East, there were opportunities at places like Bell Labs, DuPont, General Electric, IBM, and Esso. All of those giant companies had corporate labs with lots of money to do the kind of fundamental and applied research that appealed to someone like Stan Whittingham.

Among the Stanford chemists, the two most popular spots were Bell Labs and Esso. Theodore Geballe, a professor of applied physics at Stanford, had worked at Bell Labs in New Jersey during the 1950s and often helped promising young Stanford scientists find employment there and elsewhere back East.

By this time, Whittingham was ready to make a move. He and Georgina now had two kids—a two-and-a-half-year-old and a one-year-old—and he had already served more than three postdoc years at Stanford. In 1972 he received an offer from the Materials Science Department at Cornell University, but instead accepted a position with Esso. Esso had a group headed by a former Stanford chemist named Fred Gamble, and Whittingham wanted to work in Gamble's group. Esso also placed him closer to New York City, where Georgina had attended college in her undergrad years. What's more, he was getting a big salary bump to move to Esso, up to $23,000 a year. That enabled the couple to buy a nice three-bedroom house on a leafy suburban street in nearby Fanwood, New Jersey, for their growing family.

Esso was also a logical stop for a young PhD chemist. It was a mammoth company, the most recognizable of the thirty-four companies that resulted from the breakup of the Standard Oil Company in 1911. (The name Esso is a phonetic pronunciation of the "S" and the "O" in Standard Oil.) At the time, it was most notable for an ad campaign that encouraged drivers to "put a tiger in your tank." That was how the public, especially those who watched television, recognized Esso.

Shortly after he joined, however, the tiger-in-your-tank company changed its name to Exxon, and Whittingham became part of Exxon Research and Engineering Company. By the parent company's standards, Exxon Research and Engineering was considered small, so small that it didn't even warrant a mention on the annual report. That's the way it was at Exxon—anything beneath $50 million a year was considered inconsequential.

Still, Exxon Research and Engineering was big enough to take on a wide variety of cutting-edge technologies, including fuel cells, solar cells, computer chips, superconductors, and batteries, as well some non-energy projects, such as fax machines and word processors. It was also big enough to give scientists whatever they wanted in the way of equipment. When Whittingham, for example, needed "glove boxes" (a clear box with flexible sleeves) in the lab to handle hazardous materials, Exxon purchased them, no questions asked. The same held true for X-ray equipment. "In many ways, it was easier than the university," Whittingham said decades later. "If you needed equipment, they'd buy it for you. You didn't have to go get a research grant."

For the lab, energy was the common theme. Exxon Research was willing to support virtually any manner of energy research that wasn't petroleum-based. The reason for that was simple. The company's forward thinkers were hearing that the production of oil would peak around the year 2000 and then start declining. And 2000 was only twenty-eight years away.

For the Exxon parent company, the prospect of a decline in oil production was frightening. For more than a century, oil production had made Exxon and Standard

Oil very rich. In fact, it had made Standard Oil's founder, John D. Rockefeller, the wealthiest American of all time. In Standard's early years, the business had been about lighting. Kerosene made from crude oil had been a major illuminant during the 1870s.[49] Then refined oil was needed for cars and trucks when the internal combustion engine arrived in the 1880s. Later, oil found uses in reciprocating engines in airplanes, in diesel engines for train locomotives, and in outboard motors for power boats. By the middle of the twentieth century, oil had become a staple of everyday life. Interstate highways connected much of the US, enabling vehicle owners to drive virtually anywhere in the country, courtesy of oil. Cities with airports allowed individuals to board jets and fly to any other big city in the world inside of one day, courtesy of oil. Buses delivered people to their jobs, ambulances delivered them to hospitals, courtesy of oil. Trucks and trains delivered any desired food, anywhere in the country, at any time of year, again courtesy of oil. Even plastics began with feedstocks derived from oil. Between 1948 and 1972, oil consumption tripled in the United States, rose by a factor of 15 in Western Europe, and increased by a factor of 137 in Japan.[50] By the early 1970s, it was safe to say that crude oil had become the single most important source of primary energy in the history of the world.

But in the early 1970s, there were signs that the oil industry's incredible run of good fortune might not go on forever. Experts were talking publicly about "peak oil," which meant that oil production would hit its peak and then begin declining. They warned that there might only be fifty years of capacity remaining. Long-held ideas about oil—particularly, that domestic oil supplies were plentiful and Persian Gulf oil was virtually limitless—were coming into question. A man named Charles T. Maxwell, an oil analyst for Cyrus J. Lawrence Inc., even warned of a more imminent dilemma. Maxwell, dubbed the "Oil Oracle of Wall Street" by the *New York Times*, had noticed that oil refining capacity was not keeping up with domestic gasoline demand.[51] Thus, he foresaw an ominous shift in the economics of oil. American oil companies, he predicted, would no longer be able to control the prices set for Arab oil, as they had so easily in the past. Instead, he said, the Arabs would set the prices themselves. And it would happen soon.[52]

All of this weighed on the executives at Exxon, which is why they were willing to invest tens of millions of dollars into high-end energy research. Research was a small price to pay for a company that truly wanted to diversify its future, as

Exxon did. It was into this setting that Stan Whittingham made his debut as part of Exxon Research and Engineering in September 1972.

Right from the beginning, Whittingham was assigned to Fred Gamble's interdisciplinary group. The group consisted of a half dozen researchers, including a physical chemist, an inorganic chemist, a couple of physicists, and Whittingham, who brought expertise in solid-state chemistry. Their lab was in Linden, New Jersey, across the street from an oil refinery.

Gamble's group happened to be working on superconductors—materials that could conduct electricity with zero resistance. In the world of energy research, superconductivity was a sort of holy grail. With superconductivity, it was theoretically possible for electrical current to pass through a loop of wire indefinitely. The hitch was that superconducting materials required a temperature at or near −459 degrees Fahrenheit. Scientists had long studied it, however, because it offered the potential for amazing energy benefits.

It didn't take long, however, before Whittingham's superconducting research effort began to morph into something else. At the time, he'd been working with a compound called tantalum disulfide, injecting potassium ions into it, when he noticed that that he was getting high-energy reactions. The research was similar to the work he'd done at Stanford—intercalating ions into layered compounds. "So I said, 'Hey, we can store energy here,'" he recalled decades later. "And that's when we got into electrochemical studies, and then into batteries. It was a direct spin-off from superconductors."

Because Exxon gave its scientists a great deal of freedom, no one objected to Whittingham's new direction. He and his colleagues therefore took advantage of the freedom and began examining the storage of energy in other layered compounds. In addition to tantalum, they tried niobium, vanadium, and titanium. It didn't take long before they identified titanium as the best battery candidate. Titanium was light, giving it the potential for high energy density. Moreover, it was abundant.

Their next decision would change the history of science. They built a titanium disulfide battery cathode (positive pole) and paired it with an anode (negative pole) made from potassium. When they found potassium to be hazardous, however, they looked for other materials and settled on . . . lithium. Lithium was another great choice for a battery. A soft, silvery material, lithium was the lightest metal and the lightest solid element in the periodic table. What's more, it was energetic. Even volatile.

Whittingham planned to use lithium in two locales within the battery. The first was the anode, a thin slip of lithium metal that served as the negative electrode. The other was the electrolyte. The electrolyte was a liquid, an organic-based solution that incorporated lithium salts. Thus, the lithium was dissolved into the solvents, becoming an electrolyte.

In truth, Exxon wasn't alone in its use of lithium. Others around the world were applying lithium to batteries. A company in Japan was making lithium carbon fluoride batteries and selling them into fishing floats. Japanese fishermen would attach the floats to their nets at night, and the batteries would supply the power to illuminate their nets in the chilly water. Similarly, American Motors was employing lithium nickel fluoride batteries to power an electric car. And Medtronic Inc. in Minnesota was using lithium–iodine batteries for its pacemakers.

But there was a key difference between Whittingham's lithium battery and the others. In Whittingham's battery, the lithium ions in the electrolyte shuttled back and forth between the anode and cathode, inserting themselves within the atomic structure of titanium disulfide. Then the lithium ions were extracted, without damaging the titanium compound. Scientists had names for the component parts. The intercalation compound was the host and the lithium ions in the electrolyte were the guests. For Whittingham, the concept of the host and guest was just an evolution of the intercalation work he had done at Stanford. But at the same time, the larger concept—the battery itself—was unique. No one else had ever built an intercalation battery using *any* kind of chemistry.

The beauty of Whittingham's new type of lithium battery was that it was rechargeable. During discharge, ions migrated from the lithium anode to the titanium disulfide cathode, creating a current that could be used to power a device outside the battery. Then, during charging of the battery, they migrated back to the anode. There, the battery stored them for later use, whenever needed. This cycle—charge, discharge, charge, discharge—was never available in any of the lithium batteries used in fishing floats and pacemakers. But it was now, thanks to the fast ion transport that Whittingham had studied at Stanford. Thus, Exxon had now created a battery that offered both significant high energy *and* rechargeability.

Moreover, all of this happened at room temperature. You couldn't say that about Ford's sodium–sulfur battery. It operated at about five hundred degrees Fahrenheit, which wasn't an ideal situation for an automobile.

Lastly, there was the issue of voltage. Nickel–cadmium, one of the more energetic battery chemistries of the day, operated at about 1.3 volts. By comparison, Exxon's new battery put out an astonishing 2.4 volts. The voltage was significant because, in essence, it provided the power to pump the ions back and forth between the anode and cathode. Thus, it yielded not only more energy and higher energy density but also a better quality of energy.

It didn't take long before it started looking like the group had stumbled onto something important. By Christmas 1972—just three months after Whittingham's arrival—they were building makeshift batteries with titanium disulfide cathodes and metallic lithium anodes. To be sure, they weren't batteries in the conventional sense. Rather, they were two thin slips of metal in a glass beaker, separated by a liquid electrolyte. But the researchers knew their work was setting the stage for a profound change in the way batteries operated.

Within Exxon, word about the battery climbed up the corporate ladder. The company was searching for an alternative to oil and here it was. It was almost impossible when looking at the new battery to not think about an electric car. It offered high energy, was rechargeable, and operated at room temperature. In early 1973, Whittingham was summoned by Exxon corporate managers in the New York City offices. "I was asked to talk to a subcommittee of the Exxon board and explain what I was doing," he said later. "Someone in research had told them what was going on. So I went in there and explained it—five minutes, ten at the most. And within a week they decided, yes, they wanted to invest in this."

Outside Exxon in the early months of 1973, the story of electric cars had begun to lose a little bit of its media luster. General Motors, Ford, and Argonne National Laboratory continued to look at promising new battery chemistries, but the hype around those efforts was diminishing. And the same was happening in other countries. Japan's Ministry of International Trade and Industry launched a $14 million project to develop five different types of electric cars,[53] and Germany planned to promote electric vehicles in metropolitan areas,[54] but the consumer press was letting out a collective yawn. They'd heard this one before.

But late in 1973, with Exxon's crew ratcheting up its battery program, the Arab nations poured accelerant onto the fizzling electric car story. It started in October with the Yom Kippur War between Israel and its Arab neighbors. The Organization of Petroleum Exporting Countries (OPEC), responding to perceived support of Israel, declared an oil embargo. It targeted Canada, Japan, the Netherlands, the United Kingdom, Portugal, South Africa, Rhodesia, and the United States. Within four months, oil prices jumped from three dollars a barrel to twelve dollars (unadjusted for inflation). At the pump, gasoline jumped to the unheard-of figure of fifty-five cents a gallon. Panic ensued. Politicians called for gasoline rationing. President Richard Nixon asked retailers not to sell gas on Sundays, and most complied. Many placed flags in front of their stations. Green flags meant the stations had gas; yellow restricted sales to commercial vehicles; red meant out of gas. Almost overnight, lines formed around gas stations and fights broke out.

In the US, the oil embargo created a genuine sense of panic among legislators and industrial associations, which began to look for alternatives to gasoline-powered vehicles. In 1976, Congress passed a bill called the Electric and Hybrid Vehicle Research, Development, and Demonstration Act, calling for $160 million to be allotted for the creation of alternative energy vehicles. Some of that funding trickled down to places like the Electric Power Research Institute, which found matching funds from industry. Once again, the electric car was becoming a national cause. The only difference was that now, instead of being driven by air pollution, the national cause was driven by an energy crisis.

It wasn't long before stories of new battery chemistries began popping up in the press again. A group of electric utilities quickly announced they were supporting development of a zinc–chlorine battery.[55] Labs around the country ratcheted up work on sodium–sulfur, lithium–metal sulfide, nickel–iron, zinc–air, nickel–zinc, and advanced lead–acid battery chemistries.

And it went beyond battery development. More companies were now delving into electric cars. General Electric, for example, announced that it had formed a consortium to produce a "practical" electric car.[56] A Florida company built two thousand electric cars with a top speed of thirty-eight miles per hour and a range of forty miles and began selling them for $3,000 apiece.[57] American Motors provided Jeep-sized electric vans to the US Postal Service. And Sears Roebuck got in on the action, too, saying it had created an experimental electric car with the futuristic-sounding name of the XDH-1.[58]

All of that action, however, seemed tame by comparison to an emerging story from General Motors. In September 1979, the *Chicago Tribune* published a front-page story with a big, bold headline, shouting, "Gasless Car by 1985: Breakthrough at GM."[59] A companion story predicted that GM would "produce about 5,000 vehicles in the first year" and added that Ford Motor Company would "likely follow GM in 1986 or so with an electric car."[60] The article went on to predict that there would be 150 million vehicles on US roads in 2000, of which about 7 million would be electric.

While all this was going on, however, the automotive engineering community was remaining conspicuously quiet about the prospects for electric cars. Most engineers kept their ideas tightly buttoned up, letting loose only in engineering journals or technical conferences, where their words were less likely to be intercepted by national newspapers or magazines. There, they could express their growing pessimism. In the journal *Science*,[61] and in the Society of Automotive Engineers' *SAE Transactions*,[62] for example, authors increasingly expressed doubts about the near-term availability of batteries for commercially successful electric cars. Energy density and recharge time were the two big culprits, they said. And few believed that the Electric and Hybrid Vehicle Research, Development, and Demonstration Act of 1976 would lead to anything but more dead ends. Looking at the rise in "innovative" ideas now pouring in from outside the industry, the trade publication *Automotive News* best captured the spirit of the moment, writing, "It may be time for the loonies to start coming out of the woodwork."[63]

The sentiment behind it was not universally shared, but it was widespread: Most engineers were convinced that the public didn't understand the challenges of building a commercially successful automobile. And the most substantive issue was the power source. Few believed a suitable battery would be ready anytime soon. For that, they said, they would need a breakthrough. And as much as the country might want to put breakthroughs on a schedule, it wouldn't work that way. Breakthroughs couldn't be planned. "No one knows when an advanced battery will be ready," declared an author in *Science*, "nor what it will be."[64]

For Stan Whittingham, life at Exxon Research and Engineering was turning out to be a lot like life at Stanford. Exxon Research featured a highly academic atmosphere—groups of PhDs in small labs, surrounded by more small labs with more PhDs, mostly doing chemical and solids research. Moreover, Exxon's lab was legally considered a not-for-profit entity, so there was no pressure to produce any sort of short-term economic benefit. Whittingham could do the kind of fundamental research that he had done at Stanford and Oxford, culminating in journal publications or patents. It was as if he were working at the University of Exxon.

By 1973, Whittingham was already meeting with the company's patent attorneys to discuss his ideas for the new lithium titanium disulfide battery. He was pleasantly surprised by the technical acumen of the Exxon attorneys. Not only did they comprehend the esoteric nature of the battery science but they suggested specific patent claims that he hadn't considered. They were the ones who came up with ideas for building the battery in charged and fully discharged states, which would later offer advantages for many battery manufacturers. By the end of 1973, Exxon would be awarded a patent in Belgium. And by 1975, Exxon attorneys were filing a flurry of patents in the US.

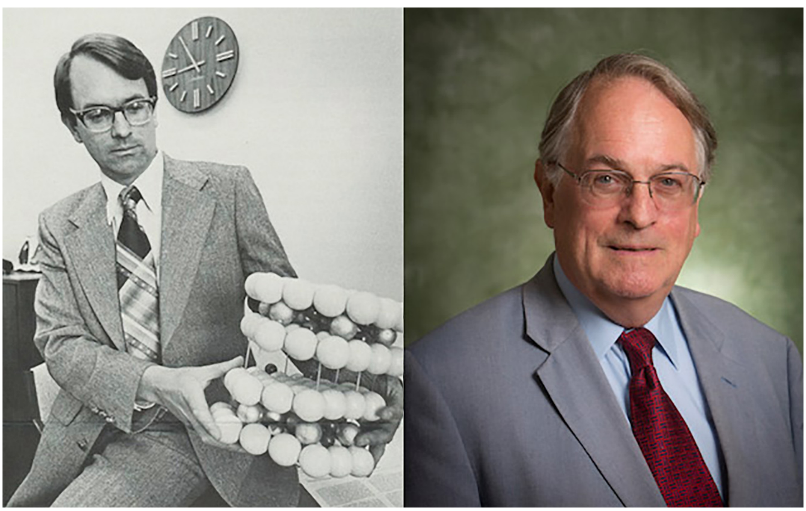
For Whittingham, the atmosphere was pure scientific bliss. No one at Exxon hovered over him, questioning his strategies or his use of funds. True, they wanted to be apprised of his results. But that was accomplished in a detached, unintimidating manner. Whittingham simply filed a report to his group head, who filed a report to *his* director, who filed a periodic report to corporate management. The process kept Whittingham almost completely insulated from the prying eyes of managers. From his perspective, the lab seemed to be run almost exclusively by engineers and scientists.

Exxon had good reasons for operating that way. Ultimately, it wanted to find alternatives to oil, and it couldn't do that if management was constantly meddling. But the company's reasoning went beyond that. Exxon corporate management felt they were in a head-to-head competition with Bell Labs, which was about twenty miles down the road in Murray Hill, New Jersey. Edward E. David, who was later named president of Exxon Research and Engineering, actually saw it as a point of pride. David had a doctorate from MIT in electrical engineering.

He had previously served as a scientific advisor to President Richard Nixon and had spent twenty years at Bell Labs. And he wanted Exxon Research to be better than Bell Labs. Better, in fact, than any corporate lab in the world. Moreover, he kept score, not by counting dollars but by counting scientific papers and patents.

In that sense, Whittingham was being a good corporate soldier from 1974 to 1979. During those years, he filed for at least fifteen patents, many related to the preparation of titanium disulfide. The culmination was a patent titled "Rechargeable Electrochemical Cell with Cathode of Stoichiometric Titanium Disulfide"[65] filed in 1976. At the same time, he published scientific papers in the *Materials Research Bulletin*, *Journal of the Electrochemical Society*, *Chemical Communications*, and ultimately *Science*.[66] The *Science* paper, published in a June 1976 edition with a stegosaurus on the cover, was his announcement to the larger technical community that Exxon was working on batteries for electric cars.

In truth, the *Science* paper said little about batteries. And it mentioned electric cars even less. Instead, there was a great deal of attention paid to the mechanics of the intercalation chemistry. But to those in the business, the signs couldn't have been more obvious. Repeated references to energy storage, charge, discharge, and



M. Stanley Whittingham in 1976 (*left*) and 2019 (*right*). His development of the lithium titanium disulfide battery at Exxon Corporation in 1972 earned him the 2019 Nobel Prize in Chemistry. (PHOTO COURTESY OF EXXON MOBIL CORPORATION.)

propulsion were like a subliminal tug on the frontal cortex of every scientist who read the publication. It had to be an electric car battery.

"It was a big deal in the world of batteries," Whittingham recalled many years later. "Some folks at Bell Labs knew what we were up to, but most people didn't have any idea that Exxon was working on batteries."

Now, however, they knew. And the announcement had been timed so that Exxon could keep its lead on whoever might dare to compete. By this time, Exxon had three groups working on the lithium titanium disulfide battery. There was the research team, which included Whittingham, an engineering team, and a manufacturing team. All signs pointed to the fact that Exxon was planning to roll out an actual product . . . a battery.

True to form, Exxon spared no expense in the creation of the engineering and manufacturing teams. Bob Hamlen, who headed the manufacturing team, came over from General Electric Research, where he'd managed the electrochemistry branch. Hamlen fit right in at Exxon, not only because he brought expertise in manufacturing but because he could talk the talk with the battery division's PhDs. He himself had a PhD in physical chemistry from Johns Hopkins University, and he experimented with his own batteries in his spare time. Hamlen loved batteries, and he was incredibly knowledgeable. At Exxon, he immediately set out to build a production battery.

Hamlen's assignment was no small task. Production batteries were altogether different than research batteries. In the research lab, a battery was essentially a couple of glass jars with liquid electrolyte and a voltmeter across them. A production battery, in contrast, had to have cans to hold the anode and cathode, preforms inside the cans, a naillike current collector, plastic seals, a separator, terminals, electrolyte, and a cover to protect the outside world from the volatile chemical reaction. Plus, a vehicle battery might also need a heat exchange mechanism, complete with liquid coolant. Finally, it also had to be manufacturable so that automated machinery could build it on an assembly line.

Making the transformation from lab battery to production battery was a big step. The first thing engineers had to deal with was the loss in energy density. Lab batteries always had great energy density numbers. But there was good reason for that. They didn't have to incorporate all the components—the cans, preforms, terminals, separators, seals, covers, current collectors, heat insulators, and cooling systems—that added dead weight to a production battery. Anything that added weight without delivering energy quite naturally lowered the energy density of the battery. Cooling systems were the worst of those, essentially doubling the weight, while adding no energy capability. In Whittingham's *Science* paper, he had acknowledged that very point, calling out a theoretical energy density of 480 watt-hours per kilogram, which at first looked spectacular. But then he added a sentence explaining that "one hundred-plus watt-hours per kilogram" might be the actual number "in a practical cell configuration." Since 1 watt-hour per kilogram equaled about a mile of driving range in an electric sedan,[67] it meant that a practical cell configuration might offer 100-plus miles of range, not 480 miles.

Hamlen's big task was to keep the energy density as high as possible, while making the battery safe. That turned out to be more difficult than anyone had anticipated. One of the reasons for its high theoretical energy density was that the battery used a metallic lithium anode. Pure metallic lithium was amazingly energetic, but it also grew dendrites, or whiskers—spikey little metallic arms that emanated outward. If the whiskers emanated too far, essentially bridging the gap between the anode and cathode, the entire battery would short-circuit. And short circuits caused fires.

The engineering and manufacturing crew had already had a few fires after they'd done postmortems on cycled batteries. They'd pull the batteries apart and—pop!—flames would erupt. There were unsubstantiated stories about firefighters coming to Linden labs on multiple occasions, repeatedly dousing fires until they finally threatened to charge the company for the special chemicals needed to extinguish the lithium blazes.[68]

Together, Hamlen and Whittingham weighed the situation and came down on the side of caution. Instead of a pure metallic lithium anode, they switched to an anode that was about two-thirds lithium and one-third aluminum. Even though the aluminum reduced the energy density, it also tempered the volatility, diminishing the possibility of fire. In July of 1976, they even put their findings into a patent, stating that "it can be advantageous to alloy the metal with other materials such as aluminum in order to minimize dendrite formation and growth during charging."[69] That strategy was not made public until the patent issued in 1977, which meant that competitors would not initially have the benefit of that knowledge, even after seeing Whittingham's paper in *Science*.

By the time the patents started issuing in 1977 and '78, Exxon was already working on building button cell batteries for a Swiss watch company, Ebauches SA. The batteries were tiny, offering either twenty-five milliamp-hours or one hundred milliamp-hours of energy, which was at best about one-twentieth of what a AA alkaline battery could have provided. But they were big enough to power Ebauches' product, a perpetual solar-powered watch. They were also rechargeable. In that way, the application actually seemed like a natural for the lithium titanium disulfide battery. Because the Exxon battery was rechargeable, it could theoretically last for many years in a wristwatch without needing a replacement. Ebauches planned to mount a little solar cell on the watch to keep the battery charged. That couldn't have been done with any garden-variety alkaline battery chemistries, which were typically not rechargeable. Moreover, Exxon engineers tested the battery in hot ovens for months and were convinced it was safe.

In many respects, prospects for the battery were looking good. The wristwatch, it seemed, was only the beginning. Hamlen believed that their rechargeable lithium battery was the best bet yet for an electric car. He and other team members took larger versions of it to various trade shows and conferences, including a Society of Automotive Engineers meeting in Chicago, to show it off. The bigger versions, measuring about six inches by four inches by an inch thick, would be placed atop a bench on the show floor and hooked up to a motorcycle headlight. There, they'd turn the light on and off all week long.

Hamlen also took every available opportunity to sell the idea at scientific conferences. He attended a 1978 meeting of the American Association for the Advancement of Science, where he declared that their battery could "make it possible to build a two-passenger electric vehicle, with an urban driving range of one hundred miles, at a cost of approximately $5,000."[70] It was an amazing statement, considering that General Motors only a few years earlier had lamented that its Electrovair with silver–zinc batteries had cost $15,000 and had given up on the vehicle for that very reason.

Still, Exxon management was not as convinced as Hamlen that the day of the electric car had arrived. There were questions about electric vehicles in general, the biggest being, Could they compete with gas-burning cars? The answer to that question wasn't clear, so Exxon assigned a group of engineers to study it. They tested an electric Jeep with lithium–metal sulfide batteries; they built an electric sports car employing lead acid batteries; and they examined the possibility of using Whittingham's lithium titanium disulfide batteries. Their conclusion was that a commercially viable electric car with rechargeable batteries was still many years away.[71]

Exxon's exploration into oil alternatives wasn't finished, however. To allay its concerns but still continue down the path to alternative energies, the company launched a plan to build a gasoline–electric hybrid car. The hybrid was seen as a bridge—a battery-based technology that could offer a temporary solution while Whittingham's team continued to work on lithium titanium disulfide.

With the hybrid, Exxon hoped to show that batteries could drastically reduce gasoline consumption. The engineering team started by buying a boatlike, four-thousand-pound 1975 Chrysler Cordoba.[72] They tore out the engine, replacing it with a four-cylinder diesel. Then they added a big battery, an AC motor, and an Exxon research device called an Electrocharger. When the car needed peak power, the battery would supply DC current, the Electrocharger would convert the DC current to AC, and the AC motor would propel the car. Like magic, they had transformed an overweight gas guzzler into a twenty-seven-mile-per-gallon gasoline hybrid vehicle.

It was a classic example of what the Exxon teams were capable of. The company was proud—so proud that it produced a glossy color brochure, complete with cutaway drawings, to show automakers. The brochure explained that the technology could boost fuel economy by 50 to 100 percent and said that it could be used for a sedan, van, or pickup. The message was clear: You can still build your big cars and get great fuel economy. "Detroit, your future can be as big and as small as America wants it," the brochure concluded.

Although most automakers ignored Exxon's glossy pitch, one saw wisdom in it. In 1979, Toyota signed an agreement calling for Exxon to convert one of its cars to a hybrid. The automaker delivered a white Toyota Cressida midsize sedan to New Jersey.[73] Exxon engineers converted it and sent it back to Toyota's research facility in Susono, Japan. Toyota took receipt of the vehicle and then went dark. (Years later, some engineers would suggest that Toyota's hybrid Cressida would serve as the company's first step toward the Toyota Prius.)

Still, everyone was happy. Exxon had proven its technology. Toyota engineers could happily crawl all over their new Cressida hybrid and reverse engineer it to their hearts' content. And Stan Whittingham's battery, as far as anyone knew, was still very much alive.

All was well at Exxon. Or at least it seemed that way.

No one was sure when or why it all started unraveling. Because Exxon had so successfully insulated its scientists from corporate management, it was almost impossible for them to guess what the executives in New York were thinking.

But Bob Hamlen found out. Discussing the future of the little button cells for Ebauches' perpetual watch, Hamlen made the mistake of describing it as a "neat $50 million business."[74] He was stunned to learn that management didn't think that $50 million was so neat. This was, after all, Exxon. "Hell, if that's the case, we don't want it," a manager told him. "We'll sell it off and license it out."[75]

It was the first sign that life was changing at the "University of Exxon." The lofty ideals of fundamental research and indifference to short-term profit were disappearing. Suddenly, a $50 million business was small potatoes, not even worthy of the lab's time.

No one in Exxon's upper management shared the company's economic strategy with the scientists, of course. Companies the size of Exxon didn't do that. Not back then. But the reasoning wasn't hard to see, really. After a seven-year climb, oil prices were finally flattening out. In a few months, they would even start a multiyear slide, all the way back down to where they had been in 1973.[76] At the same time, oil consumption was falling. Together, those two forces created what the press called "an oil glut." And the glut was creating an economic strain.

Suddenly, the forces that had propelled Exxon to search for energy alternatives were disappearing. The fears that had inspired the company to load its labs with PhDs, to produce more patents and write more papers than Bell Labs, to gaze out at science's distant horizon . . . those were disappearing, too. There were more immediate concerns.

Life at the Linden lab changed. The company began dismantling the battery division. Hamlen lost his job. Whittingham's lithium battery was licensed to three companies—one in Asia, one in Europe, and one in the US. The Asian company was rumored to be Sony Corporation (a fact that Sony never acknowledged). The American licensee was the Eveready Battery Company.

"There wasn't a lot of discussion," Whittingham said years later. "One day they just said, 'We're going to stop doing this.'"

Whittingham moved to chemical engineering, an area more in line with Exxon's short-term profits. There, scientists studied shale oil, a synthetic breed of oil that could be used for most of the same applications as crude. Whittingham stayed on at Exxon until 1984, gradually climbing the corporate ladder until he arrived at a level where he was no longer a hands-on scientist. He was following a boom-and-bust cycle—hiring chemists in good years and firing them in bad years. He learned he didn't like it. He departed for Schlumberger in 1984, then moved back to academia permanently in 1988, where he could be a scientist again.

Years later, he met an engineer from Eveready whose job was to weed through boxes of his battery notes and data from Exxon. It was standard procedure. When you licensed your technology, you had to give up all your data. But until that moment, Whittingham hadn't known where his baby—the lithium titanium disulfide battery—had ended up.

"It didn't really bother me," Whittingham recalled decades later. "I understood the rationale for doing it. The market (for batteries) just wasn't going to be big enough. Our invention was just too early."

Indeed, it had been too early. The auto and oil industries had both tried. They tried in the 1970s; they tried in the '60s. Even Thomas Edison had tried. And the result had always been the same. The capabilities and economics of electric cars still didn't match those of gasoline cars. The gap was still too big. The battery wasn't ready.

At the start of the 1980s, after Exxon had given up on batteries, electric car research stalled. The *New York Times* aptly captured the changing national spirit, writing, "In fact, it appears even with $120 million in federally backed research, mass-produced electric cars are still mirages, enticing but unattainable." The *Times* lamented that "no matter what happens, they are always five years on the horizon."[77]

The new pessimism toward battery-powered vehicles was growing. "When Exxon got out, the whole field got out," Whittingham said years later. "The federal government cut funding, thinking that if Exxon was not interested, then why should it be?"[78]

In the end, Whittingham would earn no profit from his invention of the lithium titanium disulfide battery, even though his name was on the patents. The lack of profit wasn't caused by any shortcomings in the battery. Forty years hence, Whittingham would still have a working clock on his desk powered by one of his batteries. What's more, he and Hamlen would eventually team up to produce a scientific paper showing that his button cells had retained more than 50 percent of their storage capacity thirty-five years after they had been built.[79] Still, the battery chemistry was never deemed suitable for commercial applications. No one in the auto industry had seriously considered it as a candidate for an electric car.

To be sure, the idea for a battery-powered car was not dead. There were still others, in labs at General Motors, Ford Motor Company, and elsewhere, who had not given up. None of those companies, however, had adopted Whittingham's idea.

To do that—to see the wisdom in a rechargeable lithium battery based on intercalation chemistry—would take a scientist, someone with a keen eye for fundamental research.

Fortunately, that scientist *did* exist. He was halfway around the world, back at Whittingham's alma mater, the University of Oxford.

2

Goodenough's Cathode

The scandal at the University of Oxford was over the hiring of an American physicist to serve as the chair of the school's Inorganic Chemistry Laboratory. At Oxford, where propriety and tradition were strong, the hiring was big news.

The new chair, John Goodenough, had arrived from Massachusetts Institute of Technology, where he'd served as a research scientist for twenty-four years. Tall and dark-haired with bushy eyebrows and black horn-rimmed glasses, Goodenough was perplexing for the chemists at the Oxford lab. With his pressed white shirts, neckties, and glasses, he looked more like a 1960s Madison Avenue executive than a professor. He also had a loud, high-pitched laugh that could burst forth at any moment, coupled with American mannerisms and colloquialisms that were a bit confusing to his new British colleagues.

But what really confused everyone was the fact that Goodenough was there at all. In the minds of many, there had really been only one candidate for the Inorganic Chemistry chair, and it wasn't John Goodenough. That candidate, the favorite, the obvious choice, had been a chemist named Geoffrey Wilkinson. If there had been a list of boxes to check off for the Inorganic Chemistry chair, Wilkinson would have had every box checked, and then some. He was considered a pioneer of inorganic chemistry. He had earned his PhD from Imperial College in London and had worked at Harvard and MIT in the US before returning to London to serve as chair of Inorganic Chemistry at Imperial College. He had also coauthored a chemistry textbook that was widely used by students around the world. What's more, he was elected a fellow of the British Royal Society, had won a Nobel Prize in 1973, and was knighted in 1976. Officially, he was Sir Professor Geoffrey Wilkinson. His ascendance to the Inorganic Chemistry chair at Oxford was such a foregone conclusion that he hadn't even bothered to apply for the position. He, like everyone else in the UK chemistry community, just knew the position was his to take.

In contrast, John Goodenough was a physicist, not a chemist. He had taken a total of two college chemistry classes in his life. At MIT, he had been a research scientist at the Lincoln Laboratory, a facility physically separated from the actual school. He had not served as a professor and had managed only two PhD students and one master's student in his twenty-four years there. Although he was a guest lecturer on occasion, he had not taught classes at MIT. Over the course of his career, he had published about 75 peer-reviewed papers, compared to roughly 275 for Wilkinson. By 1976, his papers were getting about 150 citations a year, compared to 600 for Wilkinson. And, of course, he was a physicist, not a chemist. For years after his appointment at Oxford, he told people that he "had to pretend" to be a chemist. Worse, he was an American.

Around the UK chemistry community, the hiring of Goodenough had been more than a head-scratcher. It was seen as a violation. "There was a sense of scandal in the inorganic chemistry community outside Oxford when an American physicist was appointed," wrote Russell Egdell, who was a PhD student at Oxford at the time.[1]

But Oxford, of course, had good reasons for making such a controversial choice. Goodenough was seen as a man with knowledge of the theoretical underpinnings of science. He possessed an enormous knowledge of the electronic structure of matter. And his résumé was amazing. He had graduated summa cum laude in mathematics from Yale University and earned a PhD in physics from the University of Chicago. At Chicago, he had worked under Nobel laureate Enrico Fermi, who demonstrated the first self-sustaining nuclear chain reaction under the school's football bleachers in 1942. He had also studied under John A. Simpson and Edward Teller, both of whom served on the Manhattan Project. His doctoral advisor had been Clarence Zener, a physicist whose name would later be familiar to virtually every electrical engineer on the planet. After Chicago, Goodenough moved to MIT's Lincoln Lab, where he was part of a team that developed the world's first random access magnetic memory, which turned out to be a critical component in the history of computing. The breadth of his knowledge was also astonishing; he could talk authoritatively about topics ranging from magnetism to superconductivity to fuel cells.

Given Goodenough's reputation, the decision-makers at Oxford weren't concerned about his lack of a formal chemistry background. Rather, they viewed his background as solid-state physics, which strongly overlapped with solid-state chemistry. It was a cutting-edge field of science, a field in which Oxford already had a strong tradition. And it was a tradition the school wanted to build upon. In contrast, Wilkinson's background was organometallic chemistry, which was not exactly what Oxford's chemistry department needed. So while the Oxford department chiefs acknowledged that Wilkinson was "the more obvious candidate as he was British," they also recognized that "Goodenough, with a strong knowledge of theory, was more suitable in this respect, more of an intellectual."[2]

There were also those who said the decision had been more than a matter of comparing résumés. There was the matter of personalities. Wilkinson was abrasive and direct. Raised in a working-class setting, he'd grown up with a fiery ambition and wanted to dominate his field of organometallic chemistry. At one point, he had bluntly advised a work colleague, a person he viewed as a competitor, to "get out of my field." And such comments were not uncommon for him. As such, some said his presence would not be welcomed at Oxford. In contrast, Goodenough's personality was an unknown commodity. He was known only as a visitor.

Still, Goodenough's appointment didn't sit well with the UK's chemistry community. Most of the community, even outside of Oxford, sided with the "practical man"—Wilkinson. Wilkinson's textbook was valuable for the majority of "practical chemistry students."[3] His approach was more suited to students who intended to go directly to industry, rather than on to advanced degrees.

No one felt the effects of the debacle more than Geoffrey Wilkinson. Although he hadn't bothered to apply for the position (since he assumed it was his anyway), Wilkinson was said to be bitter about the snubbing for the rest of his life. For years afterward, he bristled every time he heard Goodenough's name. He told anyone who would listen that Goodenough was a "second-rate electrical engineer." He believed he'd been insulted twice—once when he was edged out by a physicist, and again when that physicist turned out to be an American. Moreover, many in the chemistry community shared his sentiment. Inside and outside of Oxford, many considered Goodenough's appointment an insult.

Therefore, while Goodenough's appointment to the Inorganic Chemistry chair was an important moment for him, it did not mean he was embarking on a life of bliss. Oxford was an intimidating and prestigious school, a collection of independent colleges routinely ranked among the five best in the world. In the UK, it dominated virtually every imaginable field. More than two dozen British prime ministers had attended Oxford, and that group would eventually grow to include Margaret Thatcher (who studied chemistry there), Tony Blair, David Cameron, Theresa May, and Boris Johnson. At any given time, there were typically more than a hundred Oxford alumni in the House of Commons and a hundred more in the House of Lords. Moreover, many leaders from around the world had attended Oxford. Five prime ministers of Australia had studied there, as had six from Pakistan, two from Canada, and two from India. In science, Nobel Prizes were commonplace. By 2019, the school had been associated with eleven Nobel Prize winners in chemistry, five in physics, and sixteen in medicine. The list of other notables would eventually include such luminaries as physicist Stephen Hawking and US president Bill Clinton, as well as writers Oscar Wilde and J. R. R. Tolkien, poet T. S. Eliot, world-renowned miler Roger Bannister, Indian leader Indira Gandhi, and British adventurer T. E. Lawrence, better known as Lawrence of Arabia.

It was into this distinguished company that John Goodenough walked, and not just as a student or a professor, but as an appointee of a prestigious, financially endowed chair. For Goodenough, it was surprising and overwhelming. Chemistry had been taught at Oxford for more than three hundred years, all the way back to the days of the great scientist Robert Hooke, and many of the old formalities of those days remained intact. There were High Table dinners for "learned fellows," where professors were still expected to wear academic robes. There were teas with colleagues. The labs were old; the mercury-stained floorboards creaked; the ghosts of the great Oxford scientists roamed the halls. The place oozed history and social status. For Goodenough, the feeling of being out of his element was magnified by the fact that not everyone was enthralled with his appointment. Even those who received him warmly, as many colleagues did, wondered whether he'd been the right choice.

His struggles started almost immediately. The first challenge was in communicating in a terminology that his colleagues and students could understand. His lack of a chemistry background was the most significant barrier. Undergraduates found his lectures, filled with physics terminology and Americanisms, to be "impenetrable."[4] Students dropped out of his classes or just avoided them altogether. In one class, the number of students plummeted from 165 on the first day to just 8 on the second.[5] To fill the rapidly growing cadre of vacant seats, one enterprising student packed the second and third rows of the lecture hall with stuffed animals.[6] It was a message that Goodenough would never forget. Looking back forty-three years later, he quickly recalled the stuffed animals, joking that "the teddy bears managed to stay awake."[7]

Still, Goodenough believed from the outset that he belonged at Oxford. In the winter of 1975, he had been invited by the Royal Society of Chemistry to serve as a Centenary Lecturer, which had given him a chance to visit the school. And he had been impressed. So when an invitation arrived a few months later to apply for the Inorganic Chemistry chair, Goodenough had thrown his hat in the ring. He figured that if the people at Oxford had the courage to invite a nonacademic with a physics background to apply for the position, then he should follow up. Moreover, his wife saw it as a good move.

"My wife quite wisely said, 'I think, John, you'll go to Oxford,'" he recalled years later.[8]

For the rest of his life, Goodenough would view the matter in biblical terms. In the Old Testament, he said, God told Abraham to do exactly as his wife, Sarah, had instructed. Goodenough said it half in jest—but only half. He believed that the invitation, his appointment, and his wife's encouragement were proof of a destiny of sorts.

"You're supposed to listen to every word that Sarah says, right?" he recalled years later. "So I decided that was a good thing to do."[9]

In 1976, Goodenough may have felt he had a scientific destiny, but that destiny was apparent to no one early in his life.

Born in Jena, Germany, in 1922, John Bannister Goodenough was the second of four children. His father, Erwin Goodenough, was a twenty-nine-year-old student working on his doctoral dissertation at the University of Oxford at the time of Goodenough's imminent birth. He brought his wife, Helen, to Germany beforehand because the couple had been told a caesarean was needed, and he believed that German doctors understood the procedure better than the English.[10]

Erwin Goodenough, however, was neither German nor English. He'd grown up in Brooklyn and had studied at Hamilton College in New York, then at Drew Theological Seminary in New Jersey and at Garrett Biblical Institute near the campus of Northwestern University in Illinois. He'd also been trained as a Methodist minister at Harvard Divinity School before finally moving on to Oxford. After earning his PhD in history at Oxford, he brought the family back to the US, buying a house in Woodbridge, Connecticut, about eight miles from the campus of Yale University. There, he became a professor of comparative religion.

By that time, John Goodenough was one year old. And from that point forward, his life became a curious blend of privilege and deprivation. In rural Woodbridge his family owned an old, sprawling home on a five-acre lot. The home included a woodshed, icehouse, large barn, chicken coop, and a separate summer house, as well as a large veranda overlooking rows of elms and maple trees.[11]

The setting, however, was hardly idyllic for young John Goodenough. His family always seemed to be beset by money problems. The down payment for their home had actually come from his paternal grandfather, a real estate investor who also paid for Erwin Goodenough's years of education at Oxford. The result was that there always seemed to be larger, more pressing concerns. Even Goodenough's mother had little time for him.

Worse, Goodenough's parents suspected he was . . . slow. Goodenough's cognitive abilities came into question because he was suffering from dyslexia, a learning disability that was not well understood at the time. By age seven, it was evident that he was unable to read, and life became excruciating for him. "I was so frustrated that I couldn't read," Goodenough would recall many years later. "And, of course, my (older) brother read really well, and my father was a professor with a lot of books to be read. It was terrible."[12]

To deal with it, Goodenough sought solace in the natural world outside his back door. He chased butterflies, trapped woodchucks and skunks, collected salamanders and frogs' eggs, caught turtles in summer, and watched the birds flock in the prairies for their southerly flights in the fall.[13]

During that period, Goodenough struggled to learn to read. But even as he sounded out the words, his reading was mechanical. The meaning of any and all texts eluded him.

His parents, meanwhile, kept an active social schedule, complete with dinner parties and a maid to do the serving. Goodenough recalled frequently sitting on the back stairs with his dog, Mack, talking to the maid in the kitchen as she cooked the party meals.[14] On many nights, teenage babysitters put him and his younger brother and sister to sleep while his parents dined out.

Erwin Goodenough did, however, ensure his children were properly educated. He sent them to a private school in downtown New Haven, Connecticut, about a mile from his Yale office. But even there, John Goodenough did not thrive. Mostly, he looked for ways to cover up the fact that he didn't read well.[15] Teachers informed Goodenough's parents that their son might have to be held back in sixth grade, largely due to his inability to read and comprehend.

What happened next would forever be inexplicable, even for Goodenough. His father, recognizing that many of his better Yale students had been educated at a particular boarding school in Massachusetts, decided to have his son tested to see if he could earn a scholarship there. It seemed a long shot, but John Goodenough worked on his writing and reading skills beforehand, then shocked everyone by earning a scholarship to the school, known as Groton. For years afterward, Goodenough would consider it a matter of possible divine intervention. "That I was admitted to the First Form in 1934 remains a wondrous mystery," he later wrote. "It marked the beginning of a new life."[16]

The Groton School was indeed a new start for John Goodenough. The school, located about thirty miles northwest of Boston, was a six-year Episcopalian institution aimed at the aristocracy of America. It had an amazing one-hundred-acre campus of hills and meadows, a rolling river, athletic fields, tennis courts, and a boathouse, as well as classroom buildings, a dining hall, dormitories, and a Gothic chapel donated by the Rockefellers. Groton received much early support from Theodore Roosevelt's family. In 1904, while he was president, Roosevelt served as the commencement speaker there. Groton's alumni also included Franklin Delano Roosevelt and a long list of senators, congressmen, governors, mayors, ambassadors, publishers, professors, novelists, journalists, stockbrokers, and actors, as well as US secretaries of state, commerce, and defense. Fees for the school were extraordinarily high—$1,400 in 1934 (which, by virtue of inflation, would translate to about $28,000 a year in 2022). Eighty years later, Groton's endowment would be about $380 million, which would be more than many colleges and universities. Thus, it was little short of a miracle that twelve-year-old John Goodenough had been admitted to the place on a tuition-free basis.

The timing, however, had been ideal for the Goodenough family. By 1934, when Goodenough started at Groton, his grandfather's money was being wiped out by the Great Depression, which meant that his father's finances were also severely damaged. At that point, the Goodenough family wasn't just struggling to maintain their lifestyle; they were scrambling to pay ordinary bills. And for the most part, they were failing.

For John Goodenough, however, it was perfect. "When I left home at twelve, my life changed and it was a wonderful thing for me to get away from home," he said later.[17] He loved the structure—the sport coats, neckties, evening prayers, and the fact that the school was regulated by bells. One bell rang out across the school's quad at 7:00 a.m. and another signaled the beginning of chapel time.[18]

He was never homesick, not for a moment. Nor did it bother him that he was the "poor kid," the scholarship kid, cast in among the blue bloods. Goodenough liked his fellow classmates and enjoyed spending time with them. He even took it in stride when he was placed in the lowest academic level—the so-called B level. There were three academic paths at Groton—B, A, and upper-A. Goodenough described himself as being "at the very bottom, with the dummies" but said he was just happy to be at the school. "It had an aristocratic feel—by aristocratic, I mean an aristocracy of the spirit, that I responded to very much," Goodenough said later.[19]

Indeed, while he was at Groton, Goodenough came to identify with that aristocracy of spirit. He developed strong feelings about stealing, smoking, alcohol, gambling, thriftiness, hard work, animal cruelty, and the intrinsic value of physical labor. He got himself baptized and confirmed—on his own—while he was at the school. By his final year, the school's rector suggested he go into the ministry, but Goodenough didn't see that as the best path for himself.

Still, he believed strongly enough in his faith that he had the courage to diverge from the teachings of his own father. Erwin Goodenough, a renowned Yale religion professor who'd become an avowed agnostic, subscribed to the Freudian belief that faith was a projection of a person's upbringing onto their conscious mind. John Goodenough—high school graduate—disagreed. He contended that man had an innate sense of justice and personal honor, guided by the hand of God. And he would maintain that belief throughout his life.[20]

To some degree, Goodenough would always believe that his own life, and his experience at Groton, was a product of divine intervention. And to be sure, the Groton experience had transformed him. During his years there, he'd moved from a B-level student to an A, and then to an upper-A. He'd joined the choir and was an all-state end on the school's football team. He'd also gained popularity—enough so that he was invited to the homes of some of his wealthy classmates. "The distinctions between those from wealth and social status and those of us from middle-class homes arose only in discussions of vacation activities," he later wrote in his autobiography, *Witness to Grace*.[21]

In that sense, Groton became the perfect jumping-off point for his move to Yale University.

John Goodenough's college years started with a modest gift—$35 from his father to buy his freshman textbooks.[22] The gift complemented his full tuition scholarship, which came to him as the son of a Yale professor.

It was the last penny Goodenough would ever accept from his parents. Six months earlier, the couple had divorced after Erwin Goodenough announced he was leaving the family to marry his research assistant.[23] The divorce strained an already shaky family economy, especially given the fact that there were still two younger siblings attending college prep boarding schools. Thus, it was now clear that John Goodenough was on his own, both emotionally and financially.

Goodenough met his financial needs—his meals and spending money—by getting jobs. The first was as a bill collector at the Student Suit Pressing Company.[24] Each hour on the job paid for one meal, which meant he needed to work twenty-one hours for his weekly food allotment. For spending money he hustled, taking jobs grading papers and tutoring the children and grandchildren of professors.

Still, Goodenough wanted to immerse himself in school activities. Having played football in high school, he tried out for Yale's football team. But Yale's coaches were not as enthusiastic as he was. "I went out and on the third day on the gridiron, the coach came up and said, 'John, I'm really sorry but you have a scholarship and you work twenty-one hours a week in order to get your meals,'" Goodenough recalled later. "'You can't play football and work twenty-one hours and keep your scholarship. You're going to have to give something up.' So that was the end of my football hero (days)."[25]

The gentle prod away from football helped Goodenough focus more completely on academics. And it was then that he began laying the foundation for the multidisciplinary scientific patchwork that would characterize his long career. The first piece of the puzzle was mathematics. Mathematics made sense at the time, not because it was part of a grand plan but because Goodenough still didn't like to read. Even after a stellar high school career and after earning exceptionally high scores on his entrance exams, he still struggled with long texts. Goodenough therefore avoided, as much as possible, all classes with imposing reading lists. Along with his math classes, he took a course in chemistry and one in physics, as well as Latin, Greek, and psychology (a course he later described as an "intellectual insult"[26]). He also enrolled in one class in the history of religion, with his father as the teaching professor. Eventually, though, mathematics emerged as his major course of study, serving as the groundwork for a career in science that he didn't yet know would be his.

Socially, Goodenough's life was different from those of his contemporaries. That was largely due to lack of spending money. "I lived like all the rich boys, except that I didn't drink as they did," Goodenough recalled later. "I didn't buy superfluous things that they would buy. And I didn't take trips to New York, as they would. And I didn't have a date. So I didn't lack anything, but I didn't have anything extra."[27]

Still, he struggled to find a calling. With his strong religious convictions, he was convinced his life should be one of service. "I began to understand that the meaning to life is not the accolade of others, but the significance and permanence of what we serve," he wrote.[28]

He didn't have a clue about how best to serve, however, until reading a slim 1925 textbook titled *Science and the Modern World*. The book, a mixture of philosophy, science, and metaphysics, made him consider for the first time that science might be his calling. And with his math background, physics in particular emerged as his next logical step.

Soon, however, his thoughts of a calling would have to be put on hold. Halfway through his sophomore year, everything changed. In December 1941, the Imperial Japanese Navy bombed Pearl Harbor and Goodenough's Yale friends began enlisting in the military. Goodenough considered it himself until a math professor, Egbert Miles, advised him to wait. "He called me into his office and said, 'John, if I was you, I wouldn't volunteer for the Marines like all your friends,'" Goodenough recalled. "'What they need is people who know mathematics to do meteorology.'"[29]

Goodenough heeded his professor's advice and signed up to do army meteorology, which gave him another year of study. By that time, he had finished three years of college and was just a single course shy of graduation. Yale therefore granted him credit for studying meteorology in the military and awarded him a summa cum laude bachelor of arts degree in mathematics in early 1943.

Within weeks, Goodenough was a member of the US Army, riding a troop train to Grand Rapids, Michigan, to study meteorology. Eventually, he was stationed at an air base in Maine and then in Newfoundland, Canada, where he did weather forecasting for B-54s and other military aircraft flying across the Atlantic to Iceland, Scotland, and London. He quickly found himself in charge of the operations, even to the point where he was called upon to predict weather for the Allied D-Day invasion of the beachheads in Normandy, France.

After the war, Goodenough was invited to stay in the army as a meteorologist but declined. That turned out to be a fortuitous decision. In 1946, after receiving a telegram from the White House ordering him to return to Washington, DC, he was told he was one of twenty-one returning officers selected to do graduate study in mathematics or physics at either the University of Chicago or Northwestern University. The idea was to reintegrate a few promising scholars into civilian life by giving them a chance to attend grad school.[30]

For Goodenough the timing was perfect. By his own admission, he'd begun to feel lost after the war. Although he hadn't seen combat, he was nevertheless stressed and uncomfortable with the prospect of returning to civilian life. Once again, he was struggling with the idea of "who I was and what I was supposed to serve in life."[31] He'd even considered studying to be an international lawyer, a role that he later admitted would have turned out disastrously given his difficulties with reading.

But the prospect of graduate school gave him new direction. He recalled reading *Science and the Modern World* a few years earlier and remembered his thoughts about studying physics. "I believed it was what I was supposed to do—that I had a calling," he said many years later. "So I signed up."[32]

Within days, he was attending the University of Chicago. It was a choice that would place him with the most elite physicists in the world. In the 1940s, the University of Chicago was *the* location for theoretical physics. It was home base for Enrico Fermi, the physicist who created the world's first nuclear reaction, who has been called the architect of the nuclear age, and who won a Nobel Prize in 1938. It was also home to Edward Teller, the curmudgeonly "father of the hydrogen bomb," and John A. Simpson, a member of the Manhattan Project and the principal founder of the *Bulletin of the Atomic Scientists*. Simpson was also one of the world's first scientists to pursue an interest in cosmic rays.

For Goodenough, it was unbelievably intimidating. Only a few years earlier he had been the dyslexic boy who couldn't read, the student who was almost held back in the sixth grade, the collegian whose most prominent job was as a bill collector for the Student Suit Pressing Company. Now he was studying physics under Enrico Fermi, Edward Teller, and John A. Simpson.

Within a few weeks, he learned he wasn't at Yale anymore. The University of Chicago's teaching methods for physics grad students of that era were . . . different, which is to say that they weren't methods at all. Physics professors told him which textbooks to buy, then recommended he go to the library and teach himself. Professors occasionally lectured on whatever interested *them*, but they seldom discussed course material. And there were no tutors to tell the students what was important. "Old school" teaching, they called it.

After a year, it was time for an exam—*the* exam, determining whether a student could go on for a PhD. The exam was thirty-two hours long—eight hours a day for four consecutive days. Just 10 percent of prospective students passed. Goodenough tried and earned his master's degree, but he didn't do well enough to move on to his PhD. For that he would have to try again. The second time he took the exam, he almost quit. Despondent after the third day, he went out and played softball. But he gathered his courage and returned for the final day. To his surprise, he passed.

Now he was a PhD candidate. By this time, Goodenough had concluded he didn't want to follow in the footsteps of Fermi, Teller, or Simpson by studying nuclear physics. Instead, he opted for solid-state physics. Solid-state physics involved the study of the atomic characteristics of solid materials. It formed the theoretical underpinning for topics like metallurgy and materials science, which were directly related to engineering. It therefore had direct applications in transistors and semiconductors—soon to be two of the hottest topics in the scientific community. Working with his advisor, Clarence Zener (whose Zener diode is known to virtually every electrical engineer), Goodenough identified a thesis, which involved the study of metal crystals.

While doing all this, Goodenough lived in the International House, a University of Chicago living space that provided rooms and meals for grad students and visiting scholars. It was there that he met Irene Wiseman, a grad student in history who would eventually become his wife. Wiseman, who was two years younger than Goodenough, had grown up in Canada. Like Goodenough's father, her father had been trained as a Methodist minister and a professor. And, like Goodenough, she liked to debate religion and philosophy.

The next few years were a challenge for Goodenough. In his autobiography, as well as in numerous audio interviews, the words "struggle," "challenge," and "pressure" would come up repeatedly. Early in life, he'd struggled to read. At Yale, he felt pressure to achieve. Then he struggled to support himself financially. After military service, he'd struggled to find a calling. And at the University of Chicago, the high expectations of professors had posed one of his biggest challenges. At his advisor's direction, he'd had to modify, re-modify, and re-re-modify the concept for his PhD thesis. A week before his thesis defense, he'd been told his mathematical concepts were wrong; his assumptions were faulty. Somehow, though, he prevailed. He proved his ideas and defended his thesis. He was awarded a PhD.

In his own mind, however, the outcome had never been assured. It had been a struggle from beginning to end. He openly admitted that he felt "insecure" in his knowledge of physics.[33] His advisor, Clarence Zener, had even questioned whether he was ready to be a professor.

But by 1952, Goodenough had a PhD and three job offers—to be an assistant professor of physics at the University of Pennsylvania, a research fellow at Harvard, or a research engineer at MIT's Lincoln Laboratory. First, though, he considered being a minister. By this time, he was married. He and Irene had been married in 1951 at the Groton School chapel by her father. With the idea of ministry never far from his mind, he then applied for a Fulbright scholarship to study theology in England. But the application had been turned down and had come back with a note admonishing him to continue on in physics. Goodenough saw it as a sign. He didn't need to make a decision. It was being made for him.

Goodenough accepted the offer at MIT in 1952. He and Irene moved into a one-bedroom apartment along the Charles River, not far from the abandoned factory that housed the MIT Lincoln Laboratory.

Goodenough felt he was a good fit for the MIT Lincoln Lab, which did fundamental research that was supported by the US Air Force. He was comfortable there. At the Lincoln Lab, there was no need for him to pretend to be a professor. No need to feel insecure. He was a researcher, working with physicists, chemists, and engineers. He liked it.

His first big task involved the development of a memory for a digital computer. At the time, the term "computer" was always paired with the word "digital." Somehow, computers needed that extra word of description to signify that they weren't trivial. In 1952, computers didn't sit on top of a desk and they couldn't be held in the palm of a hand. They were big—even a small one was about the size of a one-car garage. And they didn't use transistors, diodes, microprocessors, integrated circuits, ROMs, or RAMs. No wee circuits with their little micro-amp currents. They were big and they used vacuum tubes that buzzed, glowed orange, and kicked out a lot of heat. And they had no memories.

After completing his PhD in physics at the University of Chicago in 1952, John Goodenough accepted a job as a research scientist at MIT's Lincoln Lab, where he remained for twenty-four years. (PHOTO COURTESY OF THE AMERICAN SOCIETY FOR ENGINEERING EDUCATION.)

An engineer at MIT, Jay Forrester, had developed a random-access magnetic memory a couple of years earlier, but it had proved to be too slow, so MIT was looking to boost the read–write cycle time of Forrester's memory. Goodenough led a team that helped show that ferrospinels—basically hard metal crystalline materials that looked like gemstones—could be used for the magnetic cores in the memory. It was, to some small degree, an extension of his PhD work. And now it was being applied to the world of engineering. The magnetic core would become a critical step in computer history, serving in supercomputers and mainframes for two decades, and then becoming the forerunner of the random-access memories that would be used in PCs and laptops.

To be sure, it was fundamental research. Goodenough's name would not appear on the patents for the magnetic core memory. But he had laid the groundwork for an interdisciplinary effort that would characterize much of his career. Goodenough would go on to do much more at the Lincoln Lab. He would develop scientific concepts for oxide materials and create magnetic super-exchange rules, known as the Goodenough–Kanamori rules. He would publish two books, *Magnetism and the Chemical Bond* in 1961 and *Les Oxydes des Métaux de Transition* (a French translation of a paper he had written in English) on metallic oxides in 1971. But many years later, he would still describe his interdisciplinary work with chemists and engineers as his legacy. He was especially proud of that. "At Lincoln Lab, in order to solve problems, we had to bring physics and chemistry together with engineering," he said later. Until then, he said, that was seldom done.[34]

Goodenough's career could have gone on that way at the Lincoln Lab, and still been a distinguished one, were it not for a confluence of outside forces that conspired to change his working life. It started in 1969, with the US Congress's passage of the Mansfield Amendment. The Mansfield Amendment forbade facilities like the Lincoln Lab from engaging in fundamental research that was not targeted at a specific engineering application. For Goodenough, whose very livelihood was fundamental research, it was severely limiting.

Still, he found a worthy outlet for his efforts. By 1970, Americans had begun to talk more about energy conservation, so he turned his focus to renewable energy. He reasoned that intermittent renewables, whether wind or solar, would need some way to convert electricity to chemical energy. He therefore began looking at ways to use electrolysis for fuel cells. He also searched for techniques to improve rechargeable battery anodes. Both seemed to be logical areas of research, given the new requirement to pursue engineering-related paths. Goodenough's research ideas gained even greater urgency in 1973, when news broke about the oil embargo. To some degree, he now saw this as a mission.

By this time, Goodenough had become aware of the sodium–sulfur battery at Ford Motor Company. He was even asked to sit on a government panel that was evaluating the Ford project. Looking into it, he learned that a Stanford University materials science professor, Bob Huggins, was studying the battery along with a young postdoc named Stan Whittingham. Since Goodenough was already slated to give a seminar at Stanford on the electrical properties of metallic oxides, he decided to drop in on Huggins. They talked briefly about the sodium–sulfur battery's beta alumina electrolyte, and Goodenough decided to look more deeply at the science behind it when he returned to the Lincoln Lab.

His work in sodium–sulfur, however, was short-lived. Back at MIT, he received news that his pursuit of energy studies would have to cease. Energy-related research was the province of the national energy labs—Argonne, Oak Ridge, and Los Alamos. As a US Air Force lab, Lincoln Lab was not eligible for it. For Goodenough, it was a deflating moment. He'd first been told he couldn't do fundamental research; now he was being told he couldn't do applied research in the area of energy. At that moment, he decided it was time to leave Lincoln Lab. For two decades, he'd been setting his own research paths. Now that wasn't possible anymore.

It wasn't long before Goodenough heard from the University of Oxford. They needed a new Inorganic Chemistry chair.

And John Goodenough needed a new challenge.

Around the time that John Goodenough began examining sodium–sulfur batteries, a chemist named Elton Cairns learned that "someone upstairs" at General Motors wanted to build and sell an electric car. In the vast corporate structure of GM in 1974, upstairs could have meant anything. Commands typically cascaded down from the vice president of research to an executive director, to a technical director, to a department head, to an engineer. So it was hard to know where the idea had originated. But in this case, the project appeared to have strong backing. He could only assume that, wherever it had come from, it had the blessing of GM's board of directors.

Cairns was a logical candidate to play a key role on the new electric car. He was a not a mechanical engineer but rather a "battery guy." At GM's sprawling Technical Center in Warren, Michigan, he was responsible for all battery and fuel cell research. A native Chicagoan, he had graduated at the top of his class in chemical engineering at Michigan Tech University. Michigan Tech was a smallish school of about five thousand students, mostly engineers, mostly male. It was located in Houghton, a tiny town on a narrow peninsula that jutted out into Lake Superior in the northern-most reaches of Michigan's Upper Peninsula, where the fierce winter winds could annually drop two hundred inches of snow. In really bad winters, enterprising engineering students there had been known to build snow tunnels between buildings. And even though Michigan Tech was located in the middle of nowhere—about a nine-hour drive from Detroit—it was a favored recruiting spot for the Big Four automakers. It was, after all, in Michigan.

And Detroit automakers liked people from Michigan. Also, it didn't hurt that Cairns had gone on to earn his PhD in chemical engineering at the University of California, Berkeley, or that he had later worked at General Electric, where he'd designed fuel cells for NASA's Gemini spacecraft, or that he had also served at Argonne National Laboratory, where he'd worked on batteries. His background was ideal for his new role.

As head of electrochemistry at GM Research Labs, Cairns was now in charge of developing a battery for the new electric car project. From the beginning, he believed that he understood GM's rationale for green-lighting the project. It was, in essence, a "crisis car." Normally, GM would never have considered building an electric production car. GM was a company run by mechanical engineers. All the program managers and chief engineers were mechanical engineers. Some of the past CEOs and chairmen had also been mechanical engineers. And no self-respecting mechanical engineer in 1974 wanted to build an *electric* car.

But only a year earlier, the Organization of Petroleum Exporting Countries (OPEC) had shocked the world by jacking up its oil prices. At the same time, experts had begun talking about "peak oil." By 2000, they said, global oil reserves would begin declining, sending prices higher again. If he were at MIT's Lincoln Lab or Exxon Labs, Cairns would have been scouring the periodic table for new materials that could change the course of history. But this wasn't MIT and it wasn't Exxon Labs. It was GM. And in this case, GM had little time for fundamental research. This was an engineering project on the verge of manufacturing. Soon, GM planned to go to production with its crisis car.

GM had built electric cars before, but not like this. Only a decade earlier, it had created a van propelled by a hydrogen fuel cell. It was called the Electrovan. After that, a GM research team had converted a Chevy Corvair to an electric car, calling it, predictably, the Electrovair. The Electrovair made for great headlines, but it used a silver–zinc battery from a company called Eagle-Picher Industries, which built products for the military. It was a great battery, if you happened to be building a fighter jet. But the cost was exorbitant and the battery only lasted for about a hundred charge–discharge cycles, and then it had to be replaced. All the engineers knew it wasn't a serious candidate for a production car. No sane consumer would buy an electric car with a battery that needed to be swapped out after only a hundred charge cycles. GM engineers knew this, of course, and never took the

Electrovair seriously. It was just one of those vehicles they could trot out to the press to show what good corporate citizens they were.

But this new vehicle, the crisis car, was another matter. The idea was to take a Chevette, a rear-engine subcompact built by Chevrolet, and electrify it. It would be called the Electrovette. And it would actually be built in volume and sold to willing consumers. By the time Elton Cairns joined the project, the battery had already been chosen. The chemistry was zinc–nickel oxide.

Zinc–nickel oxide was a good choice for a lot of reasons, but the biggest one was that it was well known. With zinc–nickel oxide, Cairns wouldn't have to spend months or years investigating new chemistries. His job was to optimize it—boost the energy density and cycle life—and then prepare it for volume manufacturing on the production lines at the Delco-Remy Division of General Motors.

By 1976, enthusiasm for the Electrovette was rising, and Cairns's group began working more closely with the Delco-Remy team. GM's actions gave Cairns cause for genuine hope. Inside the company, he could see that there was support for the project. Delco-Remy, he learned, loved the idea of the Electrovette. The Indiana-based division, which had been rolled into GM in 1918, was already familiar with zinc–nickel oxide, and it already had its own massive production lines for lead–acid batteries. It didn't take much imagination to picture the same kind of production lines being used for zinc–nickel oxide. Moreover, Delco-Remy was in position to supply the DC drive motors and the electronics for the Electrovette. For Delco-Remy, the new electric car looked like a financial windfall. If ever there was reason to believe that GM was *really* taking the Electrovette to production, it was now.

"I believed they were serious," Cairns said many years later. "At that point, they had to be if they wanted to keep manufacturing cars."

Cairns assigned about a half dozen electrochemists and materials scientists to the project, along with an equal number of technicians. At first, their job was to keep improving the battery's cells. Later, it was to prepare the zinc–nickel oxide battery for manufacturing at the Delco-Remy plant in Anderson, Indiana, about 260 miles south of the GM Technical Center in Warren. Every week, Cairns's team would send sample cells to Delco-Remy. And Delco-Remy would send a contingent of engineers up to Warren to discuss the details of manufacturing the battery in high volume.

Over time, Cairns counted himself a believer in the potential of zinc–nickel oxide. It was a more affordable version of the silver–zinc battery that GM had used on the Electrovair. But there was more to it than that. Cairns liked the fact that zinc–nickel oxide had an energy density of sixty watt-hours per kilogram, about twice that of the lead–acid. That translated to greater range—maybe as much as a hundred miles on a good day. Moreover, zinc–nickel oxide offered better deep cycling capabilities than lead–acid, which meant that you didn't have to recharge it as frequently. And the Delco-Remy team also liked the fact that the new battery could be built in flat prismatic cells, just like a lead–acid battery. That meant that the process of tooling up for manufacturing would be relatively easy.

Over the next two years, Cairns's team developed an engineered battery system—cells, seals, separators, terminals, enclosures, and all the other parts that were necessary for a production battery. Each part was designed with specific intent for high-speed mechanized assembly at Delco-Remy. The cells were flat—like a small pizza box. Each measured about nine by nine by one and a half inches and could be assembled into blocks. Inside the car, the blocks would be integrated into a big pack weighing about nine hundred pounds. The idea was for the entire system to be transferred to a pilot manufacturing line in Anderson.

By 1978, pilot production was up and running. Initially, the team in Anderson built about two hundred battery packs. Meanwhile, a team at the Tech Center in Warren began tearing down Chevy Chevettes in preparation to convert them to electrical propulsion. The completed Electrovettes were then hauled over to a GM track for road testing.

It wasn't long before the press started getting wind of the project. In September 1979, the *Chicago Tribune* ran a Sunday page-one story, complete with a splashy headline: "Gasless Car by 1985: Breakthrough at GM."[35] The story explained that the battery would last twenty thousand miles and would offer as much as a hundred miles of driving range at a top speed of fifty-five miles per hour. GM, it said, planned to have five thousand Electrovettes on the road by 1985. "It doesn't mean we'll have electric cars tomorrow, but we are on our way now," a GM executive told the newspaper.[36]

Days after the *Chicago Tribune* broke the story, the news began circulating around the country. The *New York Times* called GM's zinc–nickel oxide battery a "technological breakthrough."[37] Within a few hours, the company's stock climbed

2 percent.[38] The most telling comment, however, came in a follow-up story in the *Tribune*. There, GM president Pete Estes explained the company's rationale. "If we still had plenty of petroleum, it would be more efficient to refine it into gasoline or diesel, and burn it in an engine," he said, "but we don't have plenty of petroleum."[39]

At his new home at the University of Oxford, John Goodenough was now free to pursue the areas of research that had been closed to him at MIT's Lincoln Lab. One key area was energy-related research, and within that specialty he was particularly interested in batteries.

While working at MIT, Goodenough had served on a US Department of Energy panel that was evaluating Ford Motor Company's sodium–sulfur battery. The whole idea—fast transport of sodium ions through a ceramic electrolyte—was intriguing to Goodenough. It was a complete reversal of anything he'd seen previously. He talked to people at Stanford University about it and had even done some of his own work on super-ionic conductivity of sodium before leaving MIT.

One of the beauties of his new post at Oxford was that he could resume his earlier work. He discovered to his great pleasure that most of the lower-level teaching at Oxford was done by the dons of the university. Moreover, administrative duties, such as faculty appointments, did not overwhelm him, so he had time for the fundamental research he loved. And he now had staff to help him.

At Oxford's Inorganic Chemistry Lab, Goodenough had a small contingent of graduate students and postdocs working for him. In January of 1978, he was joined by a bright young postdoc physicist on sabbatical leave from the University of Tokyo, Koichi Mizushima. Goodenough quickly assigned Mizushima to the task of developing a solid-state electrolyte for a lithium battery. In a sense, Goodenough was combining two hot areas of research: solid-state electrolytes, like those at Ford, and lithium batteries. He was acutely aware of the growing interest in lithium around the world. He knew about the work done by Stanley Whittingham at Exxon, as well as the efforts by chemists in France and Germany in reversible insertion of lithium into metal sulfides.

Within a few weeks, however, Goodenough inexplicably changed course. He told Mizushima to work on a new cathode (positive pole) material. In particular, he said, he was interested in metal sulfides, like those used by Stanley Whittingham in the Exxon battery. At about the same time, Whittingham published a paper, *Chemistry of Intercalation Compounds: Metal Guests in Chalcogenide Hosts*, which basically offered a blueprint to the mechanics of ion insertion into lithium. It was clear to Goodenough that the leading edge of the battery community was now going in a new direction.

It wasn't long, however, before Mizushima's work got derailed again. During preparation of a material sample, a quartz ampule of metal sulfide powder burst into flame inside a furnace, leading to small fire in the lab. In the aftermath of the fire, Mizushima stopped all work on metal sulfides.

Still, Goodenough stubbornly clung to the idea of the lithium battery. He liked the idea of inserting lithium in the atomic structure of an electrode. His intention was to do the insertion at the cathode (positive pole) and, like Whittingham, use metallic lithium for the anode (negative pole). He recognized that metallic lithium was not an ideal solution. It was, after all, known to cause fires. But he ultimately decided that he was not building an entire battery or even an anode; his focus was only the cathode.

Thus, in April 1978, Goodenough instructed a small group of his postdocs to begin exploring metal oxides for use in a cathode. The group, which included Mizushima and another postdoc named Philip Wiseman, met in a small room adjacent to the lab. There, on a blackboard, they began scribbling ideas for new materials. They considered titanium, vanadium, chromium, manganese, iron, cobalt, and nickel. And it was then that Wiseman raised a key point: It was one thing to insert lithium in any material; it was another to extract it. Extraction, a necessary step in a reversible battery, could make some materials unstable. The materials could literally crumble. The key question, he said, was, "How many lithium props could you remove before the oxide roof caved in?"[40]

Under Goodenough's guidance, Mizushima worked on the project for one painstaking year. Starting with nickel, he experimented with each material, one by one. In the end, he culled the list of candidates down to two compounds: nickel oxide and cobalt oxide, which was essentially rock salt. Through the course of his research, he discovered that lithium ions could be successfully inserted and extracted in both nickel and cobalt. In fact, as much as 50 percent of the lithium could be extracted before the host material crumbled. This was great news by itself, but for Goodenough, the most astonishing discovery was that with their new cathode materials, they could create a battery cell that offered 4 volts. The voltage was unlike anything on the market. Cell voltages of the day typically fell between 1 and 2 volts. Whittingham's lithium titanium disulfide battery got 2.4 volts. No one was getting 4 volts.

Moreover, the battery's mechanism was actually somewhat simple, at least in theory. During charge, lithium ions plated themselves onto the outside of the metallic lithium anode. During discharge, they shuttled back through the electrolyte and inserted themselves into the layers of the cathode. At the same time, electrons outside of the battery moved from anode to cathode, providing electrical current to whatever device (such as a camcorder or phone) was attached.

The beauty of the new cathode material was that it could enable a lithium battery manufacturer to move beyond the metallic lithium anode. True, Goodenough's battery used a metallic lithium anode, just as Whittingham's had. But with the higher voltage, Goodenough believed that an enterprising battery manufacturer could now take the next step and dispose of the metallic lithium, replacing it with a less volatile compound, and still get sufficient voltage. The end result would be a safe battery—no whiskers, no dendrites, no short-circuiting.

Goodenough foresaw this and believed his cathode might have commercial applications in energy-related areas. Maybe in electrical grid storage, maybe even in an electric car. He and three of his postdocs teamed up to publish a paper on the discovery for the *Materials Research Bulletin*.[41]

The next step was the commercial world. Goodenough knew little about patents, lawyers, or intellectual property, but he thought the technology might have potential. Maybe, he thought, he could even contact battery manufacturers and get feedback. Or approach the university and see if it might help support a patent claim.

He admitted he was in the dark about business matters, but he was about to learn.

While Goodenough's team worked on the new cathode in England, General Motors engineers were ratcheting up for the eventual launch of an electric car.

By 1979, GM was assigning some of its best people to the Electrovette program. Ken Baker, one of the company's fastest-rising young vehicle engineers, had just been named chief engineer. Just thirty years old when he'd been assigned to the post, Baker was believed to be the youngest chief engineer in the company. Early on, after he'd led an effort to turbocharge Buick's Skylark coupe, Baker had been marked for the fast track. And now here he was, leading a high-profile project that was the talk of GM, and of Ford and Chrysler as well. Moreover, he was joined by some of the company's best powertrain engineers, who were given the task of developing a multispeed transmission for the new electric car.

The commitment to electrification within GM was so strong that even the most hardened, anti-electric vehicle engineers held no sway over the future of the program. When it came time to evaluate the Electrovette's multispeed transmission, Baker was placed under the direction of Frank Winchell, a vice president of engineering who showed open disdain for the program. With Winchell behind the wheel one sunny summer afternoon, the two drove the Electrovette around GM's sprawling Tech Center campus, testing the transmission. They ended up a mile and a half from Winchell's office when the transmission failed. In truth, the transmission was a kludgy contraption; it actually used a Black & Decker drill motor to move the transmission's shift fork. Winchell, a technically gifted but gruff old-time GM executive, turned to Baker and grumbled, "Damn thing's broke." Baker got out and rocked the car, hoping the transmission would reengage. Winchell sat behind the steering wheel, his blood pressure rising. But Baker was unable to get the transmission to work, so the two got out of the car and began walking back to Winchell's office in the steamy afternoon heat. Baker, dressed in a long-sleeve shirt and tie, perspired through his shirt as Winchell offered his opinions on the Electrovette. "All the way back, he told me how stupid the electric car was, and how naive I was to believe I had a working transmission concept," Baker recalled later. "I got dressed down a few times at GM, but never anything like that."

Still, the Electrovette persevered. Even Frank Winchell, in the wake of an angry mile-and-a-half hike, couldn't derail it. GM was committed to it, all the way up to the board of directors. The company wanted it because executives saw it as a potential business opportunity, especially for Delco-Remy. Financially, there was potential for the sale of batteries, motors, and control systems. Moreover, if the electric car was successful, GM would have an edge on all its competitors. Mostly, though, the company's executives wanted it because, for the first time in eighty years, they didn't know what the future looked like.

Baker believed in the project, in part because he still had youthful enthusiasm and in part because he'd heard all the ominous talk about the future of oil. By

1979, the world was going through a second oil shock, and crude prices were rising again. “It was a time when we were all concerned about the price and availability of oil,” he would say decades later. “The attitude was, ‘Oh God, what do we do if we lose availability?’ ”

As it turned out, though, GM would never really have to answer that question. Over the next two years, the truth crept up on GM, virtually unseen. Even as the company was unveiling the Electrovette to the world, the forces that created the new crisis car were peeling away, one by one, whether GM knew it or not. It had actually begun in 1977, when the massive Trans-Alaska Pipeline began pumping crude across an eight-hundred-mile stretch of Alaskan tundra, from oil fields in the north to storage tanks in the south. The pipeline, which was forty-eight inches in diameter, could supply as much as two million barrels of crude per day. At the same time, Phillips Petroleum discovered another major source of crude in the North Sea. Now, with these new sources coming on line, oil companies had an alternative to Middle East oil.

Meanwhile, American consumers had begun changing their habits. Demand for oil was dropping. From 1979 to 1981, consumption in the US market fell 13 percent. Even engine designers were learning—between 1978 and ’82, fuel economy of passenger cars rose from seventeen to twenty-two miles per gallon. It was a classic formula for economic change: supply was up, demand was down. And that, of course, led to an inevitable change in prices. In 1980, oil peaked at $35 a barrel, and then began a six-year downward spiral. And with the change in market forces, even the worries about peak oil began to evaporate.

It wasn’t long before the news trickled down from Wall Street’s energy analysts to the media. In June of 1981, the *New York Times* proclaimed that an “oil glut” had arrived.[42] And *Time* magazine stated that “the world temporarily floats in a glut of oil.”[43]

While that news should have made automakers cheer, it didn’t. That’s because a third, more ominous market force had entered the picture. By 1981, Detroit automakers were starting to worry openly about lagging sales. Only a few years earlier, American automakers had been selling more than ten million cars a year. But by 1981, with Japanese and German cars entering the US market in larger numbers, there were whispers about the sales figures possibly dropping as low as six million a year. As a result, layoffs were now rolling through Detroit. More than a quarter million autoworkers in the area were newly unemployed.[44] A grim chain reaction followed, as suppliers around the Midwest—Indiana, Illinois, and Wisconsin—learned that their factories were being shuttered. It wasn't long before GM talked about canceling three full-sized car lines at Buick, Oldsmobile, and Cadillac.[45]

For Ken Baker, it was a roller-coaster ride. When Baker had joined the Electrovette program, there'd been genuine excitement, and he was caught up in it. But by 1981, it became apparent that the economic forces behind the Electrovette were disappearing. At the same time, more news stories were describing the $60 million GM had spent so far on its electric car project.[46] The implication was obvious: GM was burning through cash on a questionable project when it could least afford to do so.

As if that weren't enough, Baker was now getting unsatisfactory reports about the Electrovette's battery. Zinc–nickel oxide had looked good in the 1970s, when gas prices were climbing and GM was still flush with research money. Newspapers had actually written stories about how the battery would last twenty thousand miles, seemingly unaware that consumers might not want to replace their $1,000 battery packs so frequently. Meanwhile, the lab's efforts to boost the battery's cycle life were running into snags.

"We learned that the battery had been oversold as a solution," Baker said later. "It did have the advantage of being able to deep cycle, and we knew it could be produced in volume. But it never had the cycle life that was necessary."

For the first time, Ken Baker started to wonder about the feasibility of the Electrovette. At GM, and throughout much of Detroit, the magic number had always been 250,000 vehicles. If you could build and sell that many, it was believed, the economies of scale would kick in. That's where you could start making money. But Baker had to wonder: Could anyone imagine the Electrovette reaching those kinds of numbers? Would that many consumers really want to buy a vehicle that needed a major powertrain replacement every twenty thousand miles? And if not, could GM really afford to carry a vehicle like this one during an economic recession?

For Baker, the answer was, unfortunately, no. He felt that if his team had been able to design the vehicle from the ground up, the Electrovette might have had a chance. But the fact that it was a converted Chevette, combined with the limitations of the battery, made it a weak market entry. Ultimately, he decided to tell GM's board of directors that it wasn't ready for production.

For a young chief engineer, it was an extraordinary move. At this point, the car and the battery had already reached pilot production. Chief engineers typically didn't undermine the feasibility of their own vehicles at such a late date. "To do something like that is not usually good for your career," Baker said years later.

Still, Baker felt strongly enough about it to board a plane for New York City to appear before the company's board at the fifty-story GM Building on Fifth Avenue. Here he was, a thirty-four-year-old, first-time chief engineer, standing at a podium before a board that included GM chairman Roger Smith and former GM president Jim McDonald. He laid out the data in stoic engineering fashion, explaining, "We're not where we need to be with zinc–nickel, to get the cycle life and endurance we need, and therefore the Electrovette should not go into production."

To his surprise, the board saw the wisdom in his data and his words. It's impossible to say if it was the battery, the availability of oil, the reduction in demand, the changing views on peak oil, or the growing recession that tipped the scales against the Electrovette. But it's likely all factors contributed. GM was plowing straight into the same forces that had kept the electric car down, not just for the past decade but for the past eighty years. To be sure, there were consumers who would have bought the Electrovette, despite its limitations. GM studies had shown that a battery range of one hundred miles would fulfill 90 percent of consumer driving needs.[47] Moreover, there was a belief that another decade of hard research might yield a better battery. But a key question lingered: How many dedicated consumers would sacrifice their hard-earned money for the purpose of helping the auto industry build a new market? Not enough, they concluded.

Then, too, there was the challenge of transforming an eighty-year-old oil-based culture. By this time, GM had already exceeded $33 million[48] in battery development over a decade, which most engineers privately considered wasteful. "The truth is, the mechanical engineers were very relieved not to have to work on an electric vehicle," said Cairns, who had left GM to become a professor of chemical engineering at the University of California, Berkeley, in 1978. "GM was very begrudging about relying on anything coming from anyone who wasn't a mechanical engineer." Cairns was one of many GM scientists who believed that zinc–nickel oxide could have succeeded with a few more years of hard research, but now that clearly would never happen.

GM naturally wanted to keep a lid on the story about its change of heart but found it impossible. By 1982, word about the Electrovette began trickling out to the media. In March, GM chairman Roger Smith admitted that the Electrovette had been placed on the back burner, contending that the program had been wounded but was not dead. "Now if gasoline rose to $8 a gallon, the electric car would suddenly take a giant leap forward in our product plans," he told the *Chicago Tribune* in a statement that bordered on the ridiculous.[49] "There are things beyond our control that would influence bringing the car out, such as gas prices, but we'll be ready with it. We have most of the technology in hand."

Nationally, the push for an electric car was losing steam. By April 1982, the US Congress had concluded that the ongoing push for vehicle electrification was a waste of funding. The main target of its ire was the 1976 Electric and Hybrid Vehicle Research, Development, and Demonstration Act. "The Energy Department has spent more than $180 million on the program since it was first authorized by Congress in 1976 with minimal results, mainly because of technical barriers," wrote United Press International.[50]

For Ken Baker, the Electrovette experience had served as a lesson, both professionally and technologically. He'd known all along that participation in an innovative program could have its career pitfalls, especially if it didn't pan out. And, indeed, it hadn't panned out. GM could tell the press whatever it wanted about the Electrovette still being in research, but the truth from an engineering perspective was that it was dead. And while it first appeared that Baker had emerged from the experience relatively unscathed, there were later some subtle signs that his status in the company had changed. Prior to his Electrovette experience, he'd been invited to a corporate gathering of senior managers at the posh Greenbriar Resort in West Virginia. After the Electrovette, he wasn't invited. A few years earlier, he'd been the fast-rising young vehicle engineer. Now, he was the former head of a defunct program.

Still, his Electrovette experience had given Baker knowledge and bargaining power that he didn't fully appreciate yet. He had learned lessons about electric car design—about the placement of batteries, the need for front-wheel drive, the importance of energy efficiency—that no one else knew. And he had learned lessons about the performance of batteries—their energy density, power density, cycle life, recharge characteristics, manufacturability—that would soon make him very valuable.

And whether GM knew it or not, the electric car would be back again.

By spring of 1979, John Goodenough had started to consider protecting the intellectual property behind his cathode. Goodenough's team had worked hard on the science, and he believed that his invention had commercial potential.

To an objective observer, of course, that wouldn't have been surprising. Inventors always believed in the commercial potential of their ideas, often unrealistically. But Goodenough was no novice. Now fifty-seven years old, he had spent half a lifetime in pursuit of scientific discovery. And he had earned a patent just three years earlier on a fast-ion-transport mechanism for sodium batteries. Moreover, he knew the state of the art in the battery industry. He was familiar with the latest scientific literature and breakthroughs, having visited some of the world's premier materials scientists in England, France, Germany, Spain, Switzerland, and the US. A few years earlier, he'd even been asked by the US Department of Energy to examine the Ford sodium–sulfur battery as part of an evaluation panel.

Still, commercialization was unfamiliar territory for Goodenough. He readily admitted he was neither a businessman nor a lawyer. He decided to start his trek into the business world by exploring the commercial possibilities of his scientific discovery. He wanted to know if anyone outside academia saw value in it, so he began contacting battery companies. But after writing to companies in England, the US, and the European mainland, he was amazed to find no takers. Most manufacturers simply ignored his letters. Those who responded said they just weren't interested.

His next step was to ask around at Oxford. But when he talked to other professors and administrators, he learned that Oxford wasn't concerned with intellectual property matters. Intellectual property, in the school's estimation, was a phenomenon of the commercial world. It was not a matter for academia. Universities were, in general, nonprofit institutions that existed for the purpose of disseminating knowledge, not circling the wagons around it. Among some professors, there was even a feeling that it was unbecoming for a university to delve into such matters. They chose academia to get away from that. For that reason and others, most academic institutions of the day had no offices of commercialization or tech transfer. To them, it seemed neither appropriate nor necessary.

Goodenough, however, still felt that the University of Oxford should receive credit for its time, effort, and knowledge. It should have access to licensing revenue that it could plow back into its labs. And for that, he believed Oxford would want to patent his idea.

There was, of course, another possibility available to Goodenough. He could pull the money out of his own pocket and pay for a patent himself. At the time, however, the cost of a patent was not insubstantial. There were fees for filing and legal representation. There were inevitable office actions, where an examiner rejected some of the legal claims and lawyers were called upon to respond. After two or three such office actions, the legal fees climbed. And then there was another charge for issuing the patent. By the end of it all, the costs often amounted to $10,000 or more, a significant fee for a university professor in 1979. Once in a while, an enterprising academic might bite the bullet and pay, digging deep into a bank account or borrowing from friends or family members, only to find that the concept went nowhere, commercially speaking.

Goodenough decided he wasn't going to get caught in that trap, but he felt he had one more potential avenue. He had previously collaborated with scientists at the UK Atomic Energy Research Establishment in Harwell, about thirteen miles south of Oxford. Scientifically, AERE (commonly known as Harwell) was a top-notch lab, formed in 1945 for the purpose of developing nuclear fission technology. It was staffed by some of the country's best scientists, some of whom were well known to Goodenough. He had collaborated with them on methanol fuel cells and had worked with them to obtain joint funding for battery research from the European Economic Community. They knew about his work on lithium.

When he talked to people at AERE, they were clearly interested. They sent a patent agent, a lawyer, to Oxford's Inorganic Chemistry Lab to interview Goodenough and Koichi Mizushima. They discussed the materials involved and their characteristics. They talked about how it might be employed commercially. Goodenough's understanding was that the Harwell lab would pay for the filing expenses. If the patent was licensed, the lab would retrieve its expenses first and then split any additional revenue with Goodenough and his postdocs. To Goodenough, it seemed an equitable arrangement.

On the day the two parties signed their legal agreements, Goodenough traveled to Harwell with one of his postdocs, Philip Wiseman. On the way in, Wiseman would later say, Goodenough turned to him and declared, "No one's going to get rich out of this."[51]

That assessment turned out to be half true. The lab's lawyers had seen to that. They had changed their minds, they said. Now, they would only agree to pay for patenting if Goodenough and his postdocs signed their rights away. The patent would still carry Goodenough's name. But all the royalties from any future licenses would be payable, not to Goodenough or his postdocs, but to the Atomic Energy Authority lab in Harwell. And it would remain that way for the life of the patent, which was twenty years.

At this point, Goodenough had grown tired of the process. He'd tried with battery manufacturers, to no avail. He'd approached Oxford, which was uninterested. Now he was being told that the reward for his effort was the patent itself and no more. Whatever limited proceeds trickled from his concept would be payable only to the people who shelled out the cash. And there was nothing surprising about it. Everyone in that room knew that university patents were a risk. And Goodenough, like so many university professors and inventors before him, knew that the odds were stacked against him.

Goodenough thought about all that for a minute, then picked up the pen and signed. He would spend the rest of his life trying to explain that moment. "I had no idea at the time what the bright electrical engineers would do with it," he said later. "I knew it was important, so that's why I patented it. But you can't visualize all that's going to happen."[52]

In truth, the lawyers at AERE hadn't visualized it either. But their lack of foresight wouldn't matter. Forces outside their control would make Goodenough's cathode a hot commodity. Portable computers, camcorders, and mobile phones would eventually need it. In 1990, AERE signed its first licensing agreement with Sony Corporation. Within a few years, most of the other major battery and computer manufacturers in the world would line up for licenses for Goodenough's technology. In the end, Goodenough would estimate that the Atomic Energy Research Establishment earned at least tens of millions of pounds from that patent, and probably more.[53]

The salt in the wound, however, was that Goodenough's contribution would not be recognized publicly. Media stories[54] would routinely identify AERE as the holder of the patent on the lithium-ion battery cathode (which, of course, was true). They would describe how its research had "led to a patent for a new concept in rechargeable batteries using lithium-ion electrodes." They would spin the tale of how the lab had waited patiently for years after the first patent was issued, until ultimately earning the monetary awards for its innovative spirit and foresight. Left out of the stories, however, was the fact that AERE scientists hadn't developed the cathode. Goodenough and Koichi Mizushima had. On the patent, they were listed as the inventors, *care of* the UK Atomic Energy Research Establishment.

But the Atomic Energy Research Establishment did not discourage the popular notion that it had invented the lithium-ion battery cathode. It was not about to provide details on that.

By the late 1990s, the UK Atomic Energy Authority was using its earnings to help fund a privatized spin-off company called AEA Technology PLC. The spin-off would team with Japanese manufacturers GS Yuasa Corporation and Mitsubishi Materials Corporation to build military batteries in Thurso, Scotland.

Goodenough, his postdocs, and the University of Oxford would earn nothing for the invention of the cathode. "AERE Harwell received many millions of pounds; we received nothing," Goodenough later wrote. "I was only disappointed that not even a contribution to St. Catherine's College (at the University of Oxford) was forthcoming."[55]

When Goodenough applied for a patent in 1979, however, no one had known the cathode's potential. Not really. Not even Goodenough. University inventions at the time were notorious for arriving too early in the development process. Scientists seldom considered such matters as scalability, productization, material availability, supply chain economics, and, of course, cost, in their inventions. And those matters ultimately determined whether an idea would be successful in the marketplace.

"Even today, the majority of licenses on university inventions are low-value deals on the front end," noted Les Nichols of Office of Technology Commercialization at the University of Texas, looking back on it forty years later. "The company that licenses it is going to need to know—can it be scaled up? What are the raw materials? Can they even buy those materials? They're going to need to invest the time and money and energy of their research teams to learn the answers to those questions."

In that sense, the UK Atomic Energy Authority's earnings from the patent were an extraordinary anomaly. People rarely made tens or hundreds of millions of dollars off university patents. And no one at the time could have foreseen the sudden and shocking emergence of mobile phones and portable computers. Even less likely was the emergence of the electric car. In 1979, it was a mere speck on the horizon. Inventor after inventor had tried to develop an electric vehicle battery, all unsuccessfully.

Besides, even Goodenough himself had questioned the viability of his own cathode. What worried him, he told colleagues, was the cobalt. Cobalt, he said, was costly. And he wondered if it would be readily available.

Such thoughts laid the foundation for his next wave of ideas. They set the stage for him to move away from the commercial world, where he was uncomfortable, and back to fundamental research. That was, after all, what he did best.

Fortuitously, there always seemed to be someone—like a Joe Kummer or a Stan Whittingham—on the horizon to help plant the seed for Goodenough's next big idea.

And that would again be the case in 1981.

3

Thackeray's Cathode

Not long after John Goodenough finished developing his lithium cobalt oxide cathode, a young South African chemist named Michael Thackeray sat down to write a letter to him.

Decades later, scientists would mark this particular time, 1980, as one when battery science had begun to expand in terms of scholarly attention. Whereas many serious scientists had steered clear of batteries a decade earlier, and whereas they had once considered batteries to be a low-tech phenomenon of the nineteenth century, they were now exploring the science more deeply. The oil embargo, troubles in the Middle East, and growing concerns over urban air pollution had set the stage for batteries to make a comeback. Around the world—in the UK, France, Canada, Japan, South Africa, the US—the best scientists were showing a renewed interest. They were publishing scientific papers and holding battery conferences. And the number of *lithium* battery scientists was on the rise. Whereas a conference in Belgirate, Italy, in 1972 had drawn less than a hundred scientists, there were now at least four times that many working on, and publishing papers about, fast ion transport in batteries.

In that sense, Thackeray was at the forefront of a trend. He'd been working on batteries for the better part of six years. As a researcher for the Council for Scientific and Industrial Research in Pretoria, South Africa, Thackeray had worked on high-temperature sodium chemistries for the so-called Zebra battery. He had also worked on lithium chemistries. And he had initiated studies of lithium reactions with metal oxide materials, even though his employer and his sponsors at CSIR weren't enthusiastic about the potential of that idea.

So it was that Mike Thackeray decided to write to John Goodenough. For Thackeray, who had a slightly rebellious streak, it seemed a natural decision. Thackeray was a tall, slim thirty-one-year-old, outwardly easygoing. But he had a grit to him that wasn't immediately visible. For fun, he ran marathons and ultramarathons over the hilly roads around his home. And when he believed he was right on certain matters—such as the reaction of lithium with metal oxides—he held tight to his ideas.

What's more, Thackeray knew Goodenough. He had followed Goodenough's work on sodium ion transport back in the days when Goodenough had been at the MIT Lincoln Lab. He had even visited the Lincoln Lab when Goodenough was there and in 1979 had stopped at the University of Oxford, where the two had met again. In his role as researcher, Thackeray was fully aware of Goodenough's work on sodium and lithium battery materials.

In late 1980, as Thackeray sat down to write his letter, Goodenough's stature was on the rise. Goodenough was four years into his tenure as chair of the Inorganic Chemistry Laboratory at Oxford. Increasingly, scientists around the world were becoming aware of his work on lithium cobalt oxide. Inside the electrochemistry community, he was now widely recognized for his encyclopedic knowledge of the electronic structure of matter. He knew how electrons and ions moved in and out of virtually any solid, and he was unsurpassed in the design of conductive materials. Worldwide, he was also becoming an important voice on matters involving fast ion transport.

Thackeray's message to Goodenough was simple: Having earned his PhD a few years earlier, he wanted to spend a postdoctoral year at Oxford. He didn't tell Goodenough about his ideas on lithium battery materials, but he made it clear that he wanted to learn and work in Oxford's Inorganic Chemistry Lab.

Goodenough's response was positive, but with one caveat. "John leapt at the chance," Thackeray recalled many years later. "He immediately wrote back and said, 'Come along if you can support yourself.'"

To be sure, the change would not be a simple one for Thackeray. By late 1981 he was married and the father of two young daughters, a two-and-a-half-year-old and a six-month-old. He would have to uproot the family, pack the diapers and the formula, travel six thousand miles to the north, and live in a foreign country. Somehow, though, he believed it would work. It would be a remedy for what ailed him in his job.

Besides, Thackeray considered it an adventure, and so did his wife, Lisa. Seven years earlier, he had taken a year off work with the intention of driving cross-country in a 1959 Volkswagen Beetle and then hitching a sailboat ride across the Atlantic. It hadn't exactly worked out that way—the Atlantic part of the journey had never happened, as marriage had intervened. But the spirit behind his idea, the desire to travel abroad, was still there in 1981. He saw the one-year Oxford sabbatical not only as chance to learn from a master but as an opportunity to experience Oxford. And his wife, who shared his adventurous spirit, agreed.

So it was, in October 1981, that he and his wife packed up the kids and moved to England. There, they rented a two-bedroom apartment that the university had found for them, a three-mile walk from the Inorganic Chemistry Lab.

There, working under John Goodenough, he would find out if his ideas on metal oxides had any merit.

Michael Makepeace Thackeray had been marked as a scientist from the very beginning. When his family made one of their occasional sojourns to London during his teen years, his aunt, Rachel Thackeray, had pointed to an engraving of legendary British scientist Michael Faraday on her wall. She looked at young Mike Thackeray and declared, "That's for you, Michael." It was as if, Thackeray thought, she already knew his destiny.[1]

Given his ancestry, Thackeray could have steered himself toward literature. He was a direct descendant of William Makepeace Thackeray, the author of the well-known English novel *Vanity Fair*, published during the 1840s. Somehow, though, his family's inclinations had changed in the ensuing century, and young Michael Thackeray was surrounded by science since the time of his birth in January 1949.

He grew up on the grounds of the Radcliffe Observatory, a fifty-seven-acre expanse of land outside Pretoria, South Africa, that housed a giant seventy-four-inch-diameter telescope, the largest in the Earth's southern hemisphere. The observatory was technically a part of Oxford University in the UK, although it was located about six thousand miles south of Oxford in South Africa. Thackeray's father, David Thackeray, was named the official Radcliffe Observer in 1950, when Michael was one year old. Radcliffe's grounds, with the big cylindrical observatory at the center, were home to him off and on for the next twenty-five years.

For young Thackeray, science was a way of life. His father had majored in mathematics at Kings College in the UK, subsequently had earned a PhD from the University of Cambridge Solar Physics Laboratory, and then spent a two-year fellowship at the Mount Wilson Observatory in California. For as long as he could remember, young Michael had known his home as a stopping-off point for distinguished visiting scientists, including Sir Lawrence Bragg, a British X-ray crystallographer who, with his father William Henry Bragg, won the Nobel Prize in Physics in 1915.

His home's atmosphere was thick with the spirit of science. At any moment when he was a child, Thackeray could stroll out into the observatory's garden and gaze at the moon or at Saturn through his father's three-inch-diameter telescope. The Radcliffe Observatory, being a few miles outside the city of Pretoria, had little light pollution, and the stars often sparkled brightly against the backdrop of the dark night sky. As he grew older, Thackeray was permitted to help track stars through the observatory's seventy-four-inch telescope. There were always at least three full-time astronomers living on the grounds, and Thackeray would occasionally join them and his father for all-night astronomy sessions, or for as long as he could stay awake. And when he walked back to his sprawling home on any given night, Thackeray could lay his head on his pillow and listen to the sounds of Chopin and Brahms wafting through the floorboards of his bedroom while his mother or father played the piano in the room below.[2]

In such an atmosphere, education would, of course, be second nature for Thackeray and his three siblings. Thanks to his father's rich uncle, a physician in London, Thackeray's education at private schools was paid for. He was sent to Waterkloof House Preparatory School in Pretoria, the same school that another notable South African, Elon Musk, would attend two decades later. Waterkloof House was a suburban boarding school, but Thackeray, being a local student, commuted to it every day. The school, he said, served him well. Part of its charter was to build maturity and independence in its students, and it took care to emphasize original thought, strategic reasoning, and creativity. It was an ideal place for Thackeray, who at that point already suspected he was headed for a career in science.

In 1968, Thackeray headed off to the University of Cape Town at the southern tip of South Africa after serving a compulsory year in the South African Army. At the university, he quickly found his calling. Unlike the man who later became his mentor, John Goodenough, Thackeray did not struggle to find his way. University classes appealed to the fierce scientific passion inside him. In particular, a geology course introduced him to "the beauty of the mineral world," creating an "inner calling to the field of crystallography."[3] Although it might have been an unusual insight for a college undergrad, it never seemed that way to Thackeray. He told people he felt a connection to the beauty of the crystalline world and geological history of the Earth. To Thackeray, an inner calling to crystallography seemed as normal and ordinary as any other youth's attraction to medicine. Ultimately, his inspiration would lead to a career studying crystalline materials in the field of battery science.

He, of course, didn't yet know about his impending role in the world of batteries. By mid-1973, Thackeray was finishing his master's thesis in crystallographic chemistry and packing up for his return to Pretoria. He already had lined up a job at CSIR, which was South Africa's preeminent national laboratory. There, he joined the Crystallography Division of the National Physical Research Laboratory.

The timing of Thackeray's entry into the world of research would ultimately have a profound effect on him. Shortly after joining the CSIR, the world of energy experienced a radical change. On October 6, 1973, on the eve of the holy Jewish holiday of Yom Kippur, Egypt launched a military strike on Israel. When Israel retaliated, the Arab countries responded with an economic weapon: oil. They cut production and instituted an embargo against Israel's allies. South Africa was one of those allies. Oil jumped from three dollars a barrel to twelve dollars. In the West, where there had already been a growing concern about oil-based air pollution, the effect was a widespread reconsideration of the realities of energy. Suddenly, policies toward alternative energy research changed.

In a sense, the CSIR lab was laying the foundation for Thackeray's career going forward, although he didn't know it. His supervisor, chemist Johan Coetzer, began rummaging through the scientific literature, searching for rechargeable battery chemistries that would provide more energy than the standard lead–acid and nickel–cadmium systems of the day. Given the growing concerns over oil, the idea was to develop a battery that could bring an electric car closer to reality. Coetzer identified high-temperature batteries similar to the now-famous Ford sodium–sulfur system.

At the time of Thackeray's arrival at CSIR in 1973, room-temperature lithium batteries seemed unrealistic. Stanley Whittingham had moved to Exxon the previous year but his work on lithium titanium disulfide was not yet well known. And John Goodenough's discovery of lithium cobalt oxide was still at least six years away. Thus, the idea of a viable room-temperature rechargeable lithium battery was unknown in the technical literature.

Still, the time was right for a major battery breakthrough for researchers willing to take risks on new chemistries. By the mid-1970s, as Thackeray worked to finish his PhD in solid-state chemistry at the University of Cape Town (while working remotely for the CSIR lab), Coetzer was ratcheting up his high-temperature battery efforts. Coetzer didn't like the idea of Ford's sodium–sulfur chemistry, considering it too corrosive and dangerous. But by using a microporous mineral called zeolite to house sulfur, he thought, it might be possible to reduce some of the corrosion and safety concerns of Ford's battery.

Moreover, Coetzer's enthusiasm for the zeolite chemistry was shared by industry. Anglo American Corporation, South Africa's largest mining company, wanted to get in on the ground floor of the electric vehicle business and saw the zeolite battery as a way to do that. Its executives looked at the global situation—an oil embargo involving politically unstable countries—and saw an opportunity. By the year 2000, they thought, electric cars could be an economic force and high-temperature batteries could be in high demand.

Anglo American, which had never been in the battery business, signed a research contract with CSIR to develop the technology. Suddenly, Anglo American became the CSIR's prized customer. Thackeray, who by this time had finished his PhD, was assigned to the high-temperature battery project.

From that point forward, Mike Thackeray would be a battery materials developer.

Later in Thackeray's life, a friend, looking back, would describe him as "thoughtfully impulsive."[4] It was a curiously accurate description—curious because so little of Thackeray's life was marked by impulsiveness. But those moments that had been impulsive turned out to be life changing. And he steadfastly owned those decisions in ways that impulsive people seldom do.

He was indeed thoughtful. Asked a question, he would stop to ponder, as if the engine in his brain was spinning but the clutch was in, and he wasn't going to move forward until he'd reached a satisfactory answer. Only then would he speak, and then quietly and decisively. What's more, everything he did seemed to involve a silent determination. He would go out for a run and log amazing numbers of miles, sometimes as many as forty in a single workout. In the early 1970s he recorded marathon times of less than two and a half hours, a remarkable time for the day. But even those twenty-six-mile races were not always enough for him. Fourteen times, he ran the Comrades Marathon in the KwaZulu-Natal province of South Africa, a fifty-six-mile event that included a five-thousand-foot ascent. It was, his friends said, one more example of the persistence and determination that characterized so much of what he did.

That was what made the impulsive moments so surprising. In 1974, just six months into his tenure as a researcher at the CSIR, he declared that he wanted to take a year off to sail across the Atlantic. It was an amazing declaration, especially since Thackeray was not an experienced sailor. But he was, if nothing else, determined. He ran the idea past his parents, who were reserved in their judgment but clearly perplexed and not entirely thrilled. He then spoke with a scientist who was a family friend. He, too, was puzzled. But his bosses at CSIR were willing to support an unpaid leave, so he gathered a few possessions and headed nine hundred miles south to Cape Town in his 1959 Volkswagen Beetle.

Unfortunately, he found no opportunities there. He tried the Royal Cape Yacht Club, without luck. He then drove a thousand miles northeast to Durban, South Africa. There, a young Swedish skipper offered him a berth on a thirty-six-foot sloop, where he served as a night lookout for oil tankers enroute to the Middle East. It was a beginning, but it took him only as far as Cape Town, which was where he had started out. Upon reaching Cape Town, however, his unpaid leave took a dramatic and impulsive turn. Days after meeting a former girlfriend there, he proposed marriage. The girlfriend, a prep school teacher named Lisa Kreft, accepted.

Suddenly, the Atlantic sailing journey had been transformed into a six-month honeymoon. The newlyweds traveled to England, bought a beat-up Volkswagen minibus in London, toured the UK, and then traveled to France, Belgium, Holland, Austria, Switzerland, and Italy, all while adhering to the principles of the book *Europe on $5 a Day*.

In January 1975 they returned to Pretoria. There, Thackeray officially entered the world of battery science. It was a career that Thackeray would never have imagined for himself a few years earlier. He had seen himself as a crystallographer, not a battery scientist. "The thought working on batteries when I was leaving university was the furthest thing from my mind," he said later. "Batteries were dirty. I had no interest in them whatsoever."

Still, this was his new role. And within three years, CSIR's big new customer, Anglo American Corporation, was serious about making a battery breakthrough. The company's executives were convinced there was a future for the electric vehicle, and they wanted to move the zeolite project forward. Moreover, they had every intention of protecting their intellectual property. Bars covered the windows in the battery labs and offices. Doors and gates were electronically controlled. Monthly meetings were attended by executives, scientists, engineers, and patent attorneys. Clearly, Anglo thought that CSIR was on to something, maybe something big. The project even had a code name—Zebra—for Zeolite Battery Research in Africa.[5]

During those years, Thackeray became a key member of the Zebra battery team. Undeniably, the Zebra concept was leading-edge. Therefore, Thackeray's employer did all of its research under a cloak of secrecy; researchers were under instructions not to publish any information about it, and attorneys kept watch for patentable concepts. Clearly, the technology had an air of importance.

Over time, the Zebra battery evolved and improved. Its chemistry changed. Ultimately, it used a solid electrolyte in between a sodium anode and iron chloride cathode. The result was a powerful, 2.35-volt cell. Quickly, it began to look as if CSIR had created a viable battery chemistry that could serve in electric cars.

Still, Thackeray was not convinced that CSIR was on the right track. He also felt he wasn't taking advantage of his educational strength, which was crystallography. The work that really lit a fire in him wasn't the Zebra battery. It was lithium. He launched a study of iron oxide in high-temperature lithium cells and learned that lithium cells yielded remarkably high energy.

Given what he knew, Thackeray wanted to take his iron oxide research a step further. He wanted to conduct experiments at room temperature. Moreover, the concept of room-temperature lithium electrochemistry had begun to grow internationally. There was a buzz around it. By then, Stanley Whittingham's work at Exxon had a small following around the world. And John Goodenough's work in lithium cobalt oxide had also been published.

Team members at CSIR and Anglo American, however, didn't agree. They didn't want to be sidetracked. They preferred to keep their focus on the Zebra battery.

Gradually, Thackeray's attitude toward the Zebra project soured. In meetings, he openly questioned the team's direction. "I just didn't believe the Zebra project could be successful," he recalled many years later. "I began to feel uncomfortable. There was all this doubt in my mind. I just wasn't happy."

Years later, Thackeray would admit that the Zebra battery had turned out to be far more successful than he had ever imagined. In the future, the Zebra battery would power cars on the German Autobahn and buses at the 1992 Olympics in Spain. But in 1981, he didn't foresee that potential. "I just needed a change," he said years later.

Thackeray's solution to the dilemma was to write letters. He wrote to Bob Huggins at Stanford University. He knew of Huggins's work on solid electrolytes. He also penned letters to national labs in the United States and to John Goodenough at the University of Oxford. He asked if any of them would take him as a postdoc in their labs.

Huggins didn't respond. And government labs in the US declined, largely due to restrictions having to do with South Africa's apartheid policies. They hesitated to take on anyone from South Africa. But Goodenough, who responded immediately, was happy to take him on. "Come along if you can support yourself," he wrote.

For a newly minted PhD scientist, Goodenough's response would have been equivalent to a rejection. In 1980, postdocs in the US typically received salaries of $10,000 to $15,000 a year (between $31,000 and $46,000 by 2022 standards). And Goodenough was offering nothing—zero pay. For Thackeray, though, it wasn't a problem. He wasn't a new PhD; he was an established researcher with close to six years of experience. And his employers were willing to pick up the tab for his postdoc year with Goodenough.

"CSIR was fantastic," Thackeray recalled later. "I'd been a little outspoken about the Zebra project, and I had put myself in a slightly difficult position. But when I asked, 'Can I take a year off?' they answered, 'Absolutely.'"

CSIR arranged for Thackeray's full salary to be paid while he worked at Oxford. CSIR agreed to pay one-third, Anglo-American paid one-third, and SAIDCOR (South African Inventions and Development Corporation) also picked up one-third. Thackeray was set. "It was a turning point," he said later. "Financially, I couldn't have done it otherwise."

Indeed, it was a turning point, both for Thackeray and for the CSIR. In retrospect, it would be obvious that his sponsors showed amazing foresight by supporting Thackeray's idea, given the limited promise that his lithium metal oxide work had shown. In truth, the voltage—the ability for an electrochemical cell to pump ions between the electrodes during discharge—was low. It was only 1.1 volts, whereas the upgraded Zebra battery showed 2.56 volts, so there was good reason to believe the Zebra battery had more long-term potential. Moreover, much of the world still believed that high-temperature sodium batteries, not lithium, were the future for electric cars. But Thackeray's bosses knew of Goodenough's global stature and wisely believed there might be a benefit to having their young researcher work with him.

Thus, Thackeray's employer supported him, so he and Lisa packed up their two daughters, Caryn and Anna, and moved six thousand miles north to Oxford. There, the university found a two-bedroom apartment for the family. The young couple considered it ideal—it was roughly equivalent to the one they'd had in Pretoria. Although it was a three-mile walk from the Inorganic Chemistry Lab, that didn't bother Thackeray.

As soon as he arrived for his first day at the lab, Thackeray met with Goodenough. Up to that point, he hadn't yet expounded on his ideas about iron oxides to anyone outside of CSIR. But during his first meeting with Goodenough, Thackeray decided to discuss his thinking. He explained what he had learned about lithium insertion in iron oxide at high temperature. He had even brought material samples containing iron, manganese, and cobalt with him to do room-temperature investigations. All of the samples were so-called spinels (pronounced "spin-ELLS")—crystalline metal oxide materials, essentially gemstone materials. The iron oxide spinel, he said, had shown the greatest potential.

To his surprise, Goodenough looked at him quizzically. "Why do you want to work on iron oxide?" Goodenough asked.

"Because it's cheap," Thackeray replied.

Goodenough liked the answer but still had doubts. "We had this wonderful chat," Thackeray recalled many years later. "He didn't think that spinels had a chance because they have a very stable structure. He said, 'If you look at the structure, and the space within it, there doesn't seem to be any place to put the lithium.'"

Still, Goodenough was willing to let Thackeray try to insert lithium into the spinels. Goodenough explained that he and his wife were soon leaving for a trip to India and recommended that Thackeray work on his idea while he was gone. "By all means, try," Goodenough said. When he returned, he said, they could discuss the results.

For Thackeray, it was one of those rare life moments when opportunity meets reality. But he didn't feel any pressure. "I really didn't know if anything was going to happen at room temperature," he said later. "But I took a flier. I said, 'Why not try?'"

By 1981, Ford Motor Company's sodium–sulfur battery was already almost eighteen years old yet hadn't seen use in a production automobile.

Still, Ford hadn't completely given up on it. Sodium–sulfur continued to show promise in the lab, offering higher energy density and the potential for longer driving range in an electric vehicle. There was nothing on the market to compare to it. The existing rechargeable chemistries—lead–acid and nickel–cadmium—simply weren't practical because they offered so little range. Lead–acid could power a midsize car for maybe forty miles, and nickel–cadmium wasn't much better. Moreover, no one was yet taking rechargeable lithium batteries seriously. Stan Whittingham's lithium titanium disulfide had only been used in wristwatches. And John Goodenough's lithium cobalt oxide wasn't really a battery; it was a cathode.

For those reasons, a team of scientists at Ford's Scientific Research Laboratory was still toiling away at sodium–sulfur in 1981. It was a small team—a half dozen scientists and a few technicians. And most of those were working on other projects in parallel with sodium–sulfur. The problem was, even after so many years, sodium–sulfur continued to be viewed as a long-term solution, something that *might* succeed at some unspecified time in the future. It simply wasn't a high priority for Ford. It was beginning to look like one of those ideas about which cynics joked, "It's the technology of the future, and always will be."

Still, Ford's commitment to the battery hadn't waned. The main difference now was that the hype around it had disappeared. Joe Kummer had created the first version of the battery in a test tube and then had gone on to coauthor a landmark technical paper about it, followed by a patent application. The paper had stirred interest in the tight-knit little battery community. Then it had been the subject of an unexpected publicity blitz starting in September 1966. The publicity began when Ford's president, Arjay Miller, had somewhat obliquely referenced the battery during a speech at the University of Michigan. Automakers, he said, had a responsibility to address issues of the day, such as air pollution. He then added that Ford was developing an electric car battery that might accomplish that. The battery, he said, "would offer tremendous improvement in range, performance and cost."

That was all anyone needed to hear. The next day, Miller's comments appeared in the *New York Times*.[6] It didn't matter that he hadn't mentioned a specific battery chemistry, or that he hadn't described how big the battery was, or whether it had been used in a test vehicle. The word was out, and the buzz around Detroit was growing louder by the day. As speculation grew, Ford decided it would tell its story to the media. Two weeks later, Miller held a press conference. It was, in some ways, a rare move. Auto companies always kept several dozen inventions in their labs at any given time, but they seldom convened news conferences to have their president talk about them. On this day, however, Miller offered diagrams of the sodium–sulfur battery and showed the test-tube apparatus. He explained the liquid electrodes, the solid beta alumina electrolyte, and the mechanisms by which the battery worked. Then his engineers hauled out a makeshift battery, connected it to a little motor, and ran a demonstration. Miller told reporters that he expected the first prototype electric cars to be ready by the following spring. He added that the autos would have a driving range of 150 to 200 miles. Finally, he declared that a production car could be expected in about ten years. The following day, the *New York Times* published another story about the battery, this time laying out all the diagrams and details.[7]

Not surprisingly, Miller's statements failed to stop the speculation. Much to the contrary, they fueled it. Now, the half dozen or so researchers at the Ford lab who were working on the little test-tube battery were suddenly at the center of an international media story. Kummer and his colleagues—Matthew Dzieciuch, Ron Radzilowski, Neill Weber, and Y. F. Yao—were shocked by the growing interest. They were a little group, even by research lab standards. And they were working on a radical and relatively untested idea—one that called for substantial external heat in order to work. They hadn't expected this.

Still, it wasn't all bad. Jobs at the Ford lab were highly desirable by most standards but, like many technical endeavors, they generally called for scientists to toil in obscurity. Now that was changing. Kummer and his coinventor, Neill Weber, appeared in a big, beautiful black-and-white layout in *Life* magazine,[8] posing with their test-tube battery. The *Life* piece announced that "a new super-battery developed by Ford has given Detroit and the petroleum industry a high-voltage jolt." It went on to suggest that the battery could be a much-needed antidote to the "mass asphyxiation" of American society that some scientists were predicting in fifty years. It also added that Ford "could be in the electric car business in ten years."

The article gave a wonderful publicity boost to Ford and it vaulted Kummer and his colleagues into the national limelight. Not long afterward, Weber presented a paper at a Society of Automotive Engineers conference and was peppered with questions from curious researchers at Shell Research, Esso Research, Battelle Memorial Institute, British Petroleum, Chrysler Corporation, Eaton Yale Company, and the Army Engineering R&D Lab. Everyone in the technical community, it seemed, wanted to know about sodium–sulfur.

The same happened when Matthew Dzieciuch attended a meeting of the Electrochemical Society. "I was overrun by people asking, 'Hey, what is this? What are you working on?'" Dzieciuch recalled years later. "They were saying, 'Come and have breakfast with me, come and have dinner with me.'"

Ford's battery, it seemed, was one of those rare technologies that piqued the interest of both the popular press and the scientific journals. The popular press loved to cite its potential to put an end to air pollution. At the same time, engineers and scientists were endlessly fascinated with its solid electrolyte and molten liquid electrodes. Many scientists had never heard of anything like it.

The brief fling with fame eventually died down, however, which made Kummer happier, anyway. The towering scientist actually preferred to work uninterrupted in his lab, and in the years following sodium–sulfur's rise to prominence, he stayed there, making a succession of improvements to the battery. Kummer and his colleagues were granted three patents in 1968, seven in 1969, four in 1970, eight in 1976, and three more in 1977. All were for sodium–sulfur materials and manufacturing processes. The team also published a steady stream of scientific papers, which were usually presented at conferences by Weber while Kummer remained behind in the lab.

The untold part of the story, however, was that sodium–sulfur was not powering cars, production or otherwise. In 1969, Ford acknowledged that it had tested four different electric cars: the Comuta (1967), the Berlina (1968), and Lead Wedge (1969), and the E-car (1969). The first three used conventional lead–acid batteries, like those employed for virtually every automotive starter. The fourth, the E-car, was outfitted with two types of packs—nickel–cadmium and lead–acid. But sodium–sulfur was nowhere to be found in any of Ford's prototype electric cars.

Still, sodium–sulfur research continued at the Ford lab. The company's engineers knew that the forty-mile driving range of lead–acid and nickel–cadmium wouldn't cut it in the marketplace, so sodium–sulfur maintained its "battery of the future" status. Even into the 1970s, the truth was that sodium–sulfur still hadn't made it very far beyond the test-tube stage. In essence, the battery still looked like it had in the photos of *Life* magazine: There was a test tube, almost a foot long, with a molten sodium liquid at its core. Outside the sodium was a thin tube made from beta alumina discs, and outside the beta alumina tube was another molten liquid—sulfur. The theory was that sodium ions would pass through the beta alumina and insert themselves in the sulfur, producing high voltage and high energy.

It did not use the same reaction mechanism as Stanley Whittingham's lithium titanium disulfide battery or John Goodenough's lithium cobalt oxide. Those batteries, to some degree, used intercalation (both could be described as "semi-intercalation batteries," since they employed one intercalation electrode and one metallic electrode). Still, sodium–sulfur offered high voltage and high energy, which translated to greater driving range. "We just viewed it as fast ion transport in a solid—solid ionics," Ron Radzilowski of the Ford lab said years later. "Joe [Kummer] was just looking at materials with a crystalline structure that would allow sodium or potassium or lithium ions to pass through."

Either way, it worked great in the lab. But Ford's considerable disadvantage was that its engineers would have to place these test-tube cells in a hostile environment. Specifically, the underside of a moving car. And Ford's automotive engineers weren't thrilled with the prospect of placing fragile glass cells in a car that might be traveling at seventy miles per hour. "We were making these tubes long—about ten to twelve inches," noted Dzieciuch. "And if one of those broke, which they did, then there was a lot of heat released between the sodium and the sulfur in the cell." The heat could progressively damage all the cells in the pack and, even worse, lead to a fire.

The other issue was the fact that the battery needed to be heated to more than five hundred degrees Fahrenheit, just to *begin* working. That meant every sodium–sulfur–based electric vehicle would need an onboard heating mechanism. Without the onboard heater, the battery wouldn't operate and the electric motor couldn't power the car. The jury was out on whether the five-hundred-degree heat was dangerous: Ford engineers were convinced they could make it safe; competitors were not so sure.

Either way, Ford decided it wasn't ready to place the sodium–sulfur cells in a fleet of test cars. Although it claimed the battery could produce driving ranges of 160 miles, there was no physical proof of that. A 1969 Ford press release contained a statement so bland that it was obvious to even the most optimistic reader that Ford still had no confidence in sodium–sulfur, at least for production vehicles. "On the basis of what has become known about materials problems and future applications of high-energy batteries," the press release said, "it is felt that the sodium-sulfur battery is an excellent competitor and deserves the vigorous research effort it is receiving at Ford and elsewhere."[9] That was it. No longer was Ford predicting a date for a production vehicle.

During the 1970s, especially after the oil embargo, there were continued references to Ford's sodium–sulfur battery. In 1971, Stanley Whittingham and Bob Huggins credited Ford in their seminal paper, "Beta Alumina—Prelude to a Revolution in Solid State Chemistry."[10] Technical papers of the era repeatedly referred to the chemistry, praising it for its high voltage and low cost, as well as the easy availability of its main elements. But the vexing problem was still how best to bring it to life. "There is almost universal agreement that the best pair [of elements] is the sodium-sulphur [*sic*] couple, which looks as if in practical systems it will have energy densities at least five times those of the best lead-acid battery," wrote an author in the Journal of the Royal Society of Arts in 1975. "But how do we do it?"[11]

Sodium–sulfur also lived on in the popular press. After the 1973 oil embargo, it was routinely mentioned in newspaper stories, along with such other chemistries as nickel–zinc, nickel–cadmium, and advanced lead–acid. It was also considered as a possibility after the US Congress passed the Electric and Hybrid Vehicle Development Research, Development, and Demonstration Act of 1976.

Still, the sodium–sulfur battery appeared in no production vehicles. By 1980, it was beginning to look as if Ford, and sodium–sulfur, had missed their window of opportunity. At that point, the auto industry had bigger problems. US automakers, which had already been losing share of market to Japanese manufacturers, suddenly found themselves bleeding red ink at new and unexpected levels. In October, Chrysler Corporation announced third-quarter losses of $490 million;[12] General Motors reported a third-quarter loss of $567 million;[13] and Ford announced losses of $595 million. Ford's was the biggest quarterly loss by any company in US corporate history.[14] Moreover, the bleeding wouldn't stop anytime soon. For the year of 1980, Ford would go on to lose $1.54 billion, which was the largest annual deficit in American business history at the time.[15]

For Detroit auto executives, it felt as if the world was collapsing on top of them. For them, life in the auto industry had never been like this. From the early 1950s until the oil embargo, business had been a succession of bountiful, profitable years, each seemingly bigger and better than the last. Their salaries had been big and their bonuses even bigger. Now, that was changing. They were laying off workers in droves. By mid-1980, the number of furloughed autoworkers in Detroit totaled 284,000. Worse, 210,000 of those had been furloughed indefinitely.[16] Stunned autoworkers were bailing out of the city and heading for places like Houston in hopes of getting oil industry jobs.

The same calamity also struck many mid- and high-level managers. Many found themselves not just without bonuses but without work. In a tale of the times, one enterprising executive founded a new business by driving from Detroit to Houston and back every weekend, returning with a truckful of Sunday newspapers and then selling them at inflated prices to desperate autoworkers hoping to find jobs in the Houston want ads.[17]

Soon, the economic malaise began spreading. On Western Avenue in Chicago, a twenty-four-mile urban stretch with dozens of auto dealerships, sales tanked and dealerships closed. During the first twenty days of May 1980, sales were down 48%.[18] Automakers reported that inventories were seventy-nine days deep. The news was even worse for parts suppliers around the Midwest. Tire makers—Uniroyal, Firestone, Goodyear, and B.F. Goodrich—all announced big quarterly losses.[19] Recognizing the devastation, auto executives began assessing it frankly. "The next six months of the year are going to be pure hell," pronounced Chrysler chairman Lee Iacocca.

Ford Motor Company, however, was taking the worst financial beating of all. It reached the point where the company was losing $3 million a day. And its stock had dropped to $23 a share, down from $66 shortly after the oil embargo. Even Henry Ford II, the tough-talking former head of Ford, was calling for government aid. "If a ship is sinking, you've got to fill the holes," he told a group at a business luncheon.[20]

The holes, of course, couldn't be filled with sodium–sulfur batteries. This wasn't a time to be trying out expensive new research ideas. So it was that the sodium–sulfur battery remained stranded on the workbenches in the Ford lab in Dearborn.

Still, Ford hadn't given up on it yet. With the right kind of nudge, it could return. Sodium–sulfur would be back in better times.

At Oxford's Inorganic Chemistry Lab there was a small team with a clear pecking order. John Goodenough was the commander, there was a postdoc physicist named Bill David, a postdoc electrochemist named Peter Bruce, a PhD student named Mark Thomas, and then there was Thackeray, the visiting chemist from Africa.

Thackeray quickly found that all the members of Goodenough's team were critical to his learning process. His teammates' expertise was especially important, given the fact that Thackeray was unfamiliar with the experimental techniques for evaluating lithium battery materials at room temperature. So his first order of business was to have Mark Thomas, the PhD student, show him the proper procedures. Thomas explained how the lithium cells were assembled and tested in a glove box—essentially a glass box with two flexible arms that allowed a chemist to reach inside and handle reactive materials. He also showed Thackeray the so-called glass Schlenk line for conducting and observing the chemical reactions.

The help from his new colleagues was critical because it allowed Thackeray to learn while Goodenough was away for two weeks in India. He hoped to be able to provide Goodenough with positive news upon his return.

Within a couple of days he had his first sign of success. On the Schlenk line, he mixed lithium with his iron oxide, called magnetite. Magnetite, an iron ore found in nature, is magnetic. Thackeray introduced the lithium into a glass flask containing the magnetite powder, then stirred the mixture with a magnetic stirrer. Given that the material was magnetic, Thackeray expected the material and the stirrer to cling to each other. But they didn't. "As the lithium was being introduced into the flask, I could see the particles gradually falling off the magnetic stirrer," he said many years later. "They weren't clinging. That was the first visible sign that something significant was happening." Thackeray then x-rayed the sample. The result showed unequivocally that lithium had indeed been inserted into the iron oxide spinel structure.

When Goodenough returned from his vacation, Thackeray caught him in the hallway outside his office. "Iron oxide spinel can accommodate lithium," he told

Goodenough. Goodenough gently took him by the shoulder, led him into his office, and carefully listened to the story of the new discovery. A couple of days later, Bill David, the team's physicist, appeared at Thackeray's desk. Having recently completed his PhD in crystallography, David was familiar with the analysis of powdered samples and knew the software needed to undertake such studies. Together, the two did a detailed analysis confirming Thackeray's earlier results. "The data showed that the lithium had been inserted," Thackeray said. "And the iron oxide framework had remained unperturbed by the lithiation reaction."

For Thackeray, it was an amazing moment. He realized that he had shown that lithium, surprisingly, could be inserted into metal oxide spinels at room temperature. His hunch was right. And the implications of his work were scientifically important. "I'll never forget the sensation of seeing the first X-ray diffraction pattern," Thackeray said. "Clearly, something big was happening, and it was happening fast."

Thackeray and David took their results back to Goodenough. Goodenough immediately understood what had occurred. "John had worked with ferromagnets since the early days of computing in the 1950s," Thackeray said. "He knew spinel structures inside out. And he knew there was too much iron in there to allow rapid movement of lithium, so as soon as I told him about the stability, he was on it like a shot. He just said, 'We've got to move from iron to manganese.'"

It was an amazing insight. Goodenough guessed they would have the same stability with manganese but would also produce a higher cell voltage. Thus, they repeated the experiments with manganese, this time aided by Peter Bruce, the team's electrochemist. Together, the young scientists showed that it worked. Lithium traveled unimpeded within the atomic structure of the manganese spinel. Moreover, the cell voltage—the ion-pumping capability—was up to three volts.

They'd created a new battery cathode. Goodenough, in a classic moment of understatement, evaluated the situation and concluded, "Mike, this might well have commercial significance." It was proof once again that Goodenough had better business instincts than colleagues later believed. He could see the battery's value in the market. He also recognized that this cathode could have advantages over the one he'd invented just a year earlier. It cost less, was more readily available, and was safer to use.

When Thackeray told his bosses in South Africa about the results, they quickly boarded a plane and flew to Oxford to meet with Goodenough. Technically, Thackeray was still an employee of South Africa's CSIR, even though the work had taken

Michael Thackeray (*left*) and John Goodenough (*right*) in 2017. The two collaborated on the lithium manganese oxide cathode at Oxford University in 1981. (PHOTO COURTESY OF PROFESSOR BILL DAVID, OXFORD UNIVERSITY.)

place at the University of Oxford. Moreover, the idea had initially been Thackeray's, even though he'd been guided to the result by Goodenough. For those reasons, the patent[21] covering the concept of the spinel framework would ultimately show Thackeray's name first and Goodenough's second. And the assignee—the organization that would earn the licensing fees—would be the South African Inventions Development Corporation.

Amazingly, the creation of the new cathode had occurred during Thackeray's first few weeks at Oxford. He and his wife and daughters had barely settled into their new apartment. "It all happened so quickly," Thackeray later recalled. "And here I had come for the whole year, and now everything was set. It was an amazing month."

Thackeray remained at Oxford for fifteen months, carefully characterizing the electrochemical properties of the lithium manganese oxide (LMO) cathodes. When he returned to the CSIR in South Africa in early 1983, he continued to work on LMO. CSIR researchers built cells with LMO cathodes and anodes, showing that the lithium ions could shuttle back and forth between the two electrodes.

Ultimately, the LMO cathode would become a huge commercial success—bigger than CSIR's Zebra battery. The Zebra, to be sure, would also be successful, appearing in limited production runs of Daimler-Benz cars and buses in the early 1990s. But it would ultimately lose its momentum in the late '90s, as the industry migrated away from high-temperature automotive batteries. In contrast, the LMO cathode would remain and grow. Automakers gravitated to it, not just because it provided high cell voltage but because its materials were readily available. It was also inexpensive and safe to use. In 2010—twenty-nine years after the Thackeray–Goodenough discovery—Nissan would use LMO in its Leaf electric car, while General Motors would use it as part of the battery cathode of its Chevy Volt.

In 1981, however, neither Goodenough nor Thackeray had visions of electric cars. They knew only that their new cathode design was stable and energetic, and that it might have potential in future rechargeable batteries.

Now the world had two lithium-ion cathodes.

All that remained was to build a battery.

4

The Graphite Anode

Now there were two cathodes. There was the lithium cobalt oxide cathode, invented by John Goodenough. And there was a lithium manganese oxide cathode, invented by Goodenough and Thackeray.

But there was no battery. Not really. Certainly not in a production sense. A complete battery required an anode, and that didn't exist yet, practically speaking. Stanley Whittingham's lithium titanium disulfide battery had had a metallic lithium anode and had been prone to fires. He had tried alloying it with aluminum, but that hadn't worked—at least not to the extent that anyone would seriously consider using it in a commercial product. Goodenough, meanwhile, understood the limitations and dangers of using metallic lithium anodes but employed them anyway. His goal wasn't to build a battery; he did it to show that lithium ions could be inserted within the structures of his cathode materials and that he could get a high voltage. Those were his goals. And he accomplished them while using a metallic lithium anode, and was perfectly comfortable going no further.

So now, the world had half of a rechargeable lithium battery. None of the researchers to date had believed their role was to build a whole battery. They saw their jobs as fundamental research, to lay the foundation for something bigger, something greater. They did not see themselves as battery developers, per se.

But in 1978, a young researcher in France named Michel Armand introduced a new idea. Instead of using one intercalation compound, he said, use two. One for the cathode (the battery's positive pole), one for the anode (the negative pole). Doing so made perfect sense. Up until that time, most of the high-impact research had used only one intercalation compound.

Armand called his idea the "rocking chair battery." The idea was for the guest ions, such as lithium, to shuttle back and forth between the anode and cathode, inserting and extracting themselves from *both* of the host materials during charge and discharge. Essentially, the ions would rock back and forth. He introduced the idea at a NATO conference called Materials for Advanced Batteries in Aussios, France, in 1978. It turned out to be a prophetic and memorable moment. In subsequent years, scientists would describe the concept by other names—shuttle battery, ion transfer battery—but the rocking chair name always stuck.

Battery scientists quickly followed up on the idea. In 1980, Italian scientists Bruno Scrosati and M. Lazzari validated the concept in a brief but groundbreaking paper, "A Cyclable Lithium Organic Electrolyte Cell Based on Two Intercalation Electrodes," published in 1980. Using lithium titanium disulfide and lithium tungsten oxide as electrodes, they proved that the intercalation reactions in the two host compounds were reversible. The rocking chair concept worked.

Armand was never sure how or why he conjured up the term "rocking chair" battery. "Maybe I was trying to be witty," he said. "I don't know why I chose it, but everyone remembered it."

So the goal now was to identify intercalation compounds—for either an anode or a cathode. To make the rocking chair concept work, scientists would need intercalation materials at both electrodes.

There was no shortage of candidates. Some scientists were considering sulfides. And a growing number had begun looking at graphite. Graphite was a crystalline form of carbon, which under high temperature and pressure could be converted to diamond. But it was best known for its use in pencils and lubricants.

During the 1970s, a number of scientists had begun to consider graphite as a potential intercalation material. They came from all over the world—Germany, Japan, and New Jersey in the US. And there were two in France.

One of the French scientists was Michel Armand. Armand was thirty-two years old in 1978 and just finishing up his PhD in physics. But his star had been on the rise since 1972. Back then, at the Fast Ion Transport in Solids conference in Belgirate, Italy, he had presented a paper suggesting that graphite could be combined with beta alumina to make a solid-state battery. It was an amazing proposal for the time, and it marked him as someone to watch in the community.

By 1978, Armand was still thinking of using graphite. Because this was almost two years before John Goodenough made his discovery of lithium cobalt oxide, there was no real cathode yet, and Armand believed graphite could be employed as either a cathode or an anode. He liked graphite because guest ions could be easily intercalated within its structure. Moreover, graphite was well known and plentiful. To him, it seemed the ideal alternative to the metallic lithium electrode.

It was a perfect task for him—as if he'd been born to do it. Michel Armand had grown up surrounded by science. His parents were physics and chemistry teachers. His maternal grandfather was a university science professor and his uncles on his father's side had both studied the sciences. One of his brothers was a mechanical engineer and the other, a computer scientist. In his home, science and technology was a way of life.

He had grown up in Annecy, France, a picturesque town of about fifty thousand in the southeastern part of the country, about thirty-five kilometers from Geneva, Switzerland. Surrounded by mountains, Annecy was nicknamed "the pearl of the French Alps." It was adjacent to a big mountain lake, which fed water into the canals that meandered down its main streets. Armand attended school in Annecy until he was eighteen. He then passed competitive exams and was admitted to one of the country's most selective schools, the École normale supérieure. There, he began his lifelong journey into electrochemistry.

His graduation in 1968 marked the beginning of his immersion into the world of battery science. After deciding to pursue a PhD, he received a Fulbright scholarship in 1970 and came to the US to study at Stanford University under Bob Huggins. In Huggins's little three-room lab, there were anywhere from four to six grad students and one or two postdocs, including a newly minted PhD from Oxford named Stan Whittingham. Armand had chosen Stanford because of its reputation, and because Huggins offered him a stipend to help pay his expenses, and because Armand's brother was studying mechanical engineering there.

At Stanford, the only problem with Armand was in holding him back. He was ambitious, intense, sometimes combative, and often brilliant. Soon after he arrived, he began building batteries with sodium, beta alumina, and graphite. But he butted heads with Huggins at Stanford because Armand wanted to build more batteries, and he felt Huggins's lab was too directed toward the theoretical study of fast ion transport. Thus, in 1972, after about eighteen months at Stanford, he left to finish his PhD in France.

In France he enrolled at Fourier University in Grenoble, at the foot of the French Alps. Fourier, he felt, gave him the academic freedom he needed. It was a good fit for Armand; it specialized in scientific research, but more specifically in matters surrounding electrical engineering. Grenoble, as it turned out, was considered "the cradle of electricity" in France. During the nineteenth century, engineers at the school had made use of local waterfalls to study electricity generation, and the university had maintained its focus on all matters electrical for the next century. In 1972, when Armand enrolled there, its scientists were doing significant research on batteries. Thus, he focused on batteries, and more specifically on intercalation compounds, for his PhD thesis.

While he worked on his PhD, Armand became an integral part of the battery community. Since his days at Stanford, he'd had an affinity for graphite, and that remained the case throughout the 1970s. He proposed it at the Fast Ion Transport in Solids conference in 1972 and continued to like its potential. He saw it as an intercalation compound. As early as 1974 he had begun to see work from other scientists who were studying it as well. Jürgen Otto Besenhard at Munich University of Technology published a paper suggesting that metal ions could be inserted into graphite, which was promising.[1] But there was also one chilling side to Besenhard's findings—there was a problem of so-called co-intercalation of solvents from liquid electrolytes. Co-intercalation could cause the electrode material to swell, rendering it unusable. "I knew that Besenhard had problems with some lithium and sodium intercalation into graphite," Armand recalled years later. Therefore, Armand decided not to use a liquid electrolyte.

In 1978, Armand proposed the idea of a polymer electrolyte—that is, an electrolyte that was solid, but not hard, like beta alumina. It was a soft electrolyte. That year, he applied for a French patent on the idea. The patent called for two electrodes separated by a solid electrolyte. Then, almost as an afterthought, the patent casually mentioned another material. "It had two lines in it that suggested lithium in graphite or potassium in graphite for the negative electrode," Armand recalled.

There were, of course, many other claims in the patent. But that particular claim—the graphite anode—would turn out to have historical significance, despite the fact that Armand hadn't yet built a full battery using a graphite anode.

In truth, the idea was too early, and too primitive. John Goodenough still hadn't invented the lithium cobalt oxide cathode yet. Moreover, no one had asked for this and no one would know what to do with it if it succeeded. As John Goodenough would learn in the ensuing years, the world was not ready for a rechargeable lithium battery.

But if the world one day needed it, the concept of the graphite anode was now on paper.

By 1978, the graphite anode was an idea in the air. Battery scientists discussed the concept and presented papers on it at conferences in towns like Belgirate, Italy, and Aussios, France, and Lake Geneva, Wisconsin. Since there was no Internet, they exchanged their ideas via slideshows on overhead projectors in hotel conference rooms. It was a cruder form of networking than they would have twenty years later, but it was successful. The word about graphite trickled out to the intelligentsia.

Thus, Armand was not the only one who saw value in graphite electrodes. Besenhard had published a paper mentioning it in 1974. A materials scientist named Samar Basu at AT&T Bell Labs was working on it. Hiroaki Ikeda of Sanyo Electric Co. Ltd. had also begun researching graphite electrodes in the late 1970s.

Therefore, when a young graduate student named Rachid Yazami arrived in Grenoble in the summer of 1978, the idea of a graphite intercalation electrode was no secret. Battery scientists around the world were aware of it, and the only unknown was whether the graphite electrode would be a cathode or an anode.

Yazami, however, did not arrive in Grenoble with the idea of studying graphite or even batteries, per se. Yazami was a chemist. He was a dark-haired, round-faced Moroccan with an infectious smile and no visions of grandeur. He enrolled in a pre-PhD program at the Grenoble Institute of Technology in 1978. By 1979 he was expected to declare a topic for his doctoral thesis. He really wasn't sure, though, how to go about doing that. Eventually, he decided to talk to different department heads and lab directors at the school. During the process, he noticed that most of them were passionate men—evangelists, in a sense—who often ended up trying to sell him on the pursuit of a scientific path not unlike their own. Still, he was usually less passionate about their topics than they were.

Finally, he talked to his advisor, Professor Philippe Touzain, who slid some technical papers across his desk and suggested that Yazami read them. "He was very calm," Yazami would remember forty years later. "And he told me, 'There are no good rechargeable batteries out there.'" One of the papers was on the use of graphite materials as a cathode for lithium batteries, and it was coauthored by Touzain and Michel Armand. Yazami read that paper and was intrigued by it. Moreover, he knew of the work done by Stanley Whittingham at Exxon and so understood that something important was happening in the world of batteries. "Stanley Whittingham had said that intercalation compounds would be the best materials for rechargeable batteries," Yazami said years later. "And he was right." Ultimately, Yazami concluded that the rechargeable battery was a topic worth pursuing.

Yazami hadn't foreseen himself becoming a battery scientist, but he had always expected to be a chemist. He was twelve years old when he learned he was destined for life in the laboratory. "My teacher noticed I could absorb science very quickly," he said many years later. "So one day he pointed his finger at me in class and said, 'Rachid, one day you will be a chemist.'" Yazami never forgot that moment. For the rest of his life he viewed chemistry as his calling, even when other teachers later suggested he belonged elsewhere.

The second of his family's seven children, Yazami grew up in Fez, a crowded twelve-hundred-year-old urban area of 1.2 million people in northern Morocco. A city of great beauty, Fez was dominated by ancient Islamic architecture that included Moorish arches and elaborate arabesque structures of wood and stucco. Although Morocco had been officially recognized as a French protectorate until 1956, its religious traditions had lived on, and Fez was home to more than five hundred mosques. From the age of four, children were unofficially taught to read in Arabic from the Koran. The educational facilities were crude—instead of using paper, they wrote on wooden boards with homemade bamboo pens using a mixture of clay and water for ink. But the education was sound.

Such was the case for Yazami. Although his father ran a modest distributorship of dairy products and his mother did not work outside the home, he received a strong education. By age six, when he was first officially enrolled in a school, he already knew how to read. Classes typically had forty-plus students and fifteen or so small desks, each seating three children. In the mornings they were taught by an Arabic teacher using Arabic books. At noon the students walked home for lunch, ate, swapped out their Arabic books for French books, and returned to school in the afternoon, ready to be taught by a French-speaking teacher. In that way, all kids grew up bilingual.

It was not an easy transition. Arabic books were written from right to left, while French went from left to right. Learning to read in both languages was a difficult task. But the teachers were very strict about it—children were expected to adapt, and they did. "The teacher of Arabic would be very angry if he saw you with a French book in your bag," Yazami recalled. "It was good because in a way there was a wall between the two. The Arabic teacher did not want to hear a single word of French."

His ability to speak French fluently would ultimately change his life. When it came time to attend a university, Yazami selected Mohammed V University, which was home to Morocco's only four-year science program. But there Yazami stumbled into the first challenge of his academic career. The university, located in the capitol city of Rabat, was a hazardous place in 1971 because the country was suffering through a period of political instability. "For the first time in my life, I saw the military in our streets," Yazami recalled. "I decided I couldn't stay. It was too dangerous."

He transferred to Rouen University in Normandy, France. It turned out to be a logical move for Yazami for two reasons: First, he was fluent in French; second, the school promoted the idea of international academic exchanges like his. He earned a bachelor's degree, then enrolled at the Grenoble Institute of Technology for his master's degree. There, his memory of his science teacher in Fez came back to him. "When I got to the admissions office, I gave my name and they immediately tried to put me in the applied mathematics program," Yazami said. "And at that moment, I remembered the words of my teacher in school: 'You, Rachid, will be a chemist.' So I said to them, 'No, no, I'm sorry but I want to go into chemistry." By 1978, he had earned his master's degree in electrochemistry.

What happened next may have altered the course of lithium-ion history. For reasons that are unclear, Yazami decided to study graphite intercalation. By agreement with his PhD advisor, he now had two main tasks to carry out. The first was to intercalate metal chlorides into graphite. The second was to use the resulting compound as a cathode for a lithium battery. This was to be the foundation of his PhD. But at this point, there was no thought to creating an anode.

His project, however, turned out to be exceedingly complex. The experiments were carried out under special conditions at very high temperatures—750 degrees Centigrade—and the results were less than promising. The efficiency of the chemical reactions was not high, and the reaction itself was not reversible, which did not bode well for a rechargeable battery.

At this point, Yazami began to think more about simply proving that lithium *could* be intercalated into graphite. "If you looked at the technical literature of the times, nobody was able to put lithium into graphite in an electrochemical cell without having some kind of reaction with the electrolytes," he said. "Either the electrolyte would decompose, or the graphite would expand more than 300 percent. So I was intrigued. I asked, 'Why is it not possible to intercalate lithium into graphite?'"

Thus, Yazami decided to see if lithium could be intercalated into bare graphite without any metal chlorides. This clearly was outside the boundaries of his prescribed PhD work, so he decided not to ask for permission. He just went ahead and did it. Unfortunately, Yazami found his idea didn't work. Every time he tried it, the battery's electrolyte would decompose.

Years later, Yazami's recollection would be that he decided to replace the decomposing electrolyte with Armand's soft polymer electrolyte. He said he took the polymer and created, in essence, a lithium-polymer-graphite sandwich. Then, very slowly, he attempted to run the lithium ions through the polymer and insert them into the graphite. It was a painstakingly tedious experiment, performed at high temperature and pressure, inside a so-called glove box.

Not everyone agrees on what happened next. In Yazami's version of the event, he waited for more than a month, opened the glove box, and examined his materials. To his amazement, he later said, the graphite had turned a golden color. It was a sign, and he knew what it meant. Graphite, by nature, wasn't gold; it was black. The golden color meant that the lithium ions had inserted themselves within the layers of the graphite. Yazami said he then uttered a word normally reserved for scientists in low-budget movies. "I jumped to the ceiling and actually yelled, 'Eureka!'" he recalled. In his excitement, he said, he began running around the lab. He visited his advisor's office and also claimed that he told Armand of his success. Armand, however, would not recall the moment.

Today, some historians and scientists question whether Yazami's golden compound was a product of electrochemical intercalation. Nothing published by Yazami at the time indicates that it was, they say. Still, Yazami said he used an X-ray diffractometer to take pictures. Sure enough, he would later claim, the lithium was in there, inserted between the layers of graphite.

In subsequent descriptions, Yazami said he understood that for the discovery to have real meaning, he would have to show that the lithium ions could be *de*-intercalated, or extracted, from the graphite. If they could, it would mean that they could travel back and forth, and that graphite could be used for a rechargeable lithium battery. A rocking chair battery.

Thus, he says he set out to perform the experiment in reverse. He put the materials back in the glove box at high pressure and high temperature, then waited for another month. When he checked it a month later, the graphite was no longer golden. It was black. The lithium ions, he said, had de-intercalated.

Yazami would always describe this as another amazing moment. He again ran to his advisor and asked whether he should publish a paper about his finding or file for a patent. The advisor told him to patent it first, then write a paper. So here he was, a twenty-six-year-old student just a few months into his PhD work in late 1979, and he was already about to file for a patent. And the technical paper would soon follow.

The project was, to be sure, outside the realm of his PhD work. His PhD called for him to intercalate lithium into graphite for a cathode. But he decided it would not work for a cathode. Cathode materials needed to offer high voltage to be practical. Whittingham's titanium disulfide cathode had offered about 2.5 volts. Goodenough's lithium cobalt oxide would later offer 3.7 volts, and a metal chloride cathode created by Touzain and Armand had provided 3.6 volts. But this new compound was less than a volt, which made it better suited for an anode.

So Yazami had invented not a cathode but an anode. Following the suggestion of the school's advisors, he wrote a report detailing the finding and explaining how it could be used as an anode in a lithium battery. The report was filed to the French National Center for Scientific Research, which incorporated a technology transfer group called Anvar. Anvar, in turn, called Yazami's advisors and recommended that a patent be filed.

"I was really happy," Yazami said later. "Here it was, less than a year after I had joined the PhD program, and already I had an invention."

A few weeks later, the technology transfer group called again and said they planned to file the patent under the name of a local battery company called Saft. Saft was a half-century-old international company that made batteries for power plants, telephone systems, and aviation, among other applications. Its most profitable chemistry had been alkaline, but it had started to branch into nickel–cadmium rechargeable batteries. The plan was for Saft to file the patent and own the license and, in return, sponsor Yazami's continued work at the university. On the surface, it looked like a win for all involved: Saft would draw the licensing fees, Yazami would have a patent, and the university would have research funds.

There was, however, one big difficulty: Executives at Saft weren't interested. No one was sure why (many theories were put forth), but Saft had strong negative feelings about the concept. "They wanted to kill the project," Yazami said many years later. "They wrote a flaming report saying they had no applications for lithium batteries and had no interest in a license. The gentleman from Anvar [the technology transfer office] said that if the company thinks this graphite anode has no future then, sorry, but we're not going to file a patent."

Suddenly, Yazami's great finding—the intercalation of lithium into graphite—was no longer a great finding. But he was young and still a few years from earning his PhD. Yazami's advisors encouraged him to publish, which he did. In June 1982, he described his anode in a paper titled "A Reversible Graphite-Lithium Negative Electrode for Electrochemical Generators," submitted to the *Journal of Power Sources*.[2] It would eventually be recognized as a landmark paper, the first to definitively describe a graphite intercalation anode. In subsequent years, Yazami presented the topic at many technical conferences and became recognized as an evangelist of sorts for the graphite anode.

Whether he would be considered the inventor of the graphite anode, however, would always be a matter of debate. In retrospect, some scientists in the battery community doubted that he had inserted lithium ions into graphite. The voltage, they said, was too low for such intercalation. They knew *something* had happened, but they weren't sure what. For his part, Yazami would always claim that his experiment had succeeded, and his X-ray diffraction data had proved it.

Yazami would later be honored for his work on the graphite anode. He would go on to receive the 2014 Charles Stark Draper Prize (the "Nobel of engineering") for it. But in retrospect, it would be impossible to historically recognize any individual as *the* single inventor. In November 1980, Samar Basu of Bell Labs filed for a patent[3] for his rechargeable battery, noting that "the negative electrode is lithium intercalated in graphite." In the patent, the word "graphite" would be used forty-one times. Rumors would abound that Bell Labs licensed the patent to a Japanese manufacturer, possibly earning as much as $100 million. Meanwhile, Sanyo researchers had also begun filing for a family of patents involving graphite anodes in 1981. Sanyo built batteries with graphite anodes about a decade later. Then there was also Besenhard's scientific paper[4] in 1974 and Michel Armand's patent in 1978.[5] Armand would later remind historians that he'd preceded his countryman by more than a year, and had in fact called it out in a patent, even though he hadn't built a full battery. So the fact remained that no single scientist could ever be identified as *the* inventor. It was, in the truest sense, an idea in the air.

Moreover, it didn't matter in the early 1980s. The reality at the time was that the graphite anode appeared to be a journey down a blind alley. If it were used in liquid electrolytes of the day, the graphite would swell. It would grow by about 300 percent. It would co-intercalate solvents. Researchers could, of course, eliminate those issues by pairing it with a solid electrolyte, but the battery community was clearly not ready for solid electrolytes yet.

Nor was it ready for the graphite anode. It had been an interesting little scientific exercise, nothing more. Members of the battery community knew that graphite wasn't ready for practical application at the time, and possibly not ever.

Or so they thought.

Jeff Dahn did not set out to solve the electrolyte problem. Dahn was seven years removed from having earned his PhD and was working for a start-up company called Moli Energy when he and his coworkers stumbled upon an elemental truth that seemed to have occurred to no one in the battery community up until then. The irony was that Dahn made his discovery while searching for something else.

Dahn had come to Moli Energy because he wanted to develop batteries and because he knew the company's founder. As director of research at Moli, Dahn's job was to screen every kind of carbon he could get his hands on, including graphite, for the purpose of building a lithium intercalation battery.

For Dahn, the task was well suited to his background. Dahn had grown up in Nova Scotia, Canada, in a little harbor town called Lunenburg along the Atlantic

Ocean. It was not the kind of rich academic environment that was so common to many of the battery community's most notable scientists. Lunenburg's Center Consolidated School was very small and had no fast-track science classes for gifted students. Most of the young males in Lunenburg dropped out of school in the ninth or tenth grade to work on the local fishing boats. But Dahn's father was a mechanical engineer and his mother had a master's degree in English from Columbia University, so he was bound to follow a more academic path. He earned a bachelor's degree in physics at Dalhousie University and then went west to graduate school at the University of British Columbia. There, he did his PhD thesis on lithium intercalation materials. At the time, he had a special interest in Stanley Whittingham's titanium disulfide. During his doctoral studies, the school purchased a bound volume of Exxon's work on the intercalation battery. The big blue volume was about the size of a city phone book and was packed with Exxon's scientific papers. "It was like a Bible for us in the beginning," Dahn later said. "The Exxon team did really nice work."

His knowledge of Exxon's work, as it turned out, was critical for his work at Moli Energy. Moli was doing a variation on Whittingham's work, replacing his titanium with a material that was cheaper and more plentiful. The material was molybdenum (the name Moli was an acronym for molybdenum lithium). Thus, the cathode for Moli's battery would be molybdenum disulfide.

At the same time, Moli's research team also considered a wide range of carbon materials. It looked at soft carbons made from petroleum coke. And it examined various commercially available graphites, which it purchased from Conoco Research.

That was where the accidental discovery occurred. In 1987, while working with graphite, Moli's research team tried various types of liquid electrolytes. Up to that time, most liquid electrolytes had consisted of lithium salts, dissolved in a mixture using propylene carbonate (known as PC). But Moli was trying out different types of blended electrolytes. One was a fifty-fifty blend of PC and another solvent called ethylene carbonate (known as EC). The researchers quickly learned that the PC-based electrolyte didn't work with graphite. It caused co-intercalation and swelling of the material—a phenomenon already well known throughout much of the battery community.

But they also discovered that the fifty-fifty blend of EC and PC worked with graphite. No co-intercalation. No side reactions. No swelling. "The fifty-fifty blend was readily available, so we kept using it," Dahn said. "It was like bottled water for us."

Whether the Moli scientists knew it or not, it was a major milestone for the rechargeable lithium battery. Up until that time, most of battery community had viewed PC and EC as virtually identical, with one notable exception: EC had a higher melting point. Thus, EC had long ago fallen into disfavor,[6] and PC had become the liquid electrolyte of choice. But here was evidence that they were not the same, and that EC actually enabled the use of graphite. "We were surprised and didn't really understand why ethylene carbonate and propylene carbonate were so different," Dahn recalled later. "They're essentially the same molecule."

They were, however, *very* different in a lithium battery, especially one with a graphite anode. In 1990, Dahn coauthored a paper, "Studies of Lithium Intercalation into Carbons Using Nonaqueous Electrochemical Cells," describing Moli's discovery.[7] It's not known how many others knew of the advantages of EC by that time (although it had been mentioned in various patents), but Dahn's was the first paper to broadly deliver the knowledge to the community.

Within a year, a team of engineers headed by Hiroaki Ikeda at Sanyo filed for the first patent on an EC-based electrolyte for a rechargeable lithium battery. Again, it's not known if Ikeda was working on the electrolyte before Dahn, or whether one of Sanyo's engineers saw Dahn's publication. But it turned out well for Sanyo, which had been granted a patent a decade earlier for a lithium battery using a graphite electrode. In the 1980s, the earlier patent had seemed like a trip down a blind alley. But now the two patents fit neatly together. Sanyo now had a patent on the graphite anode *and* an on EC-based electrolyte that made graphite a real possibility. So while Dahn would later be credited with scientifically explaining why EC must be used, Sanyo engineers would be credited with the patenting of the EC-based electrolyte for the graphite anode.

For the battery community, it changed everything. By 1993 the community had become aware of the merits of electrolytic solutions that contained EC, and not PC. And with that awareness, graphitic carbons, offering lower cost and higher energy, became the norm. The EC-based electrolyte would later serve as the foundation of the mainstream rechargeable lithium battery. By 2020, there would be billions of graphite anodes in lithium-ion batteries for laptops, cars, and cell phones, as well as hundreds of other products. And virtually all used an EC-based electrolyte.

Still, it hadn't initially been big news to Jeff Dahn or to the other researchers at Moli Energy in 1987. It was merely an insight gleaned in the course of normal research. "We didn't go around saying, 'EC is wonderful,'" Dahn said later. "We were using it from the beginning. We were just kind of lucky."

Now, another piece of the puzzle was in place.

5

Japan's Battery

The day that the commercial version of the rechargeable lithium battery started to come together was New Year's Eve, 1982. Akira Yoshino, a chemical researcher at the Asahi Chemical Corporation in Japan, was cleaning his office on that day, trying to get ready for a fresh start in the new year. The previous few months had been stressful for him, Yoshino would later write.[1] He and his colleagues had spent more than a year developing a battery anode and then, after concluding they had found the right material, Yoshino had realized that he had no viable cathode to pair with it.

But on that New Year's Eve as he shuffled the papers on his desk, Yoshino noticed something important, a technical publication titled "A New Cathode Material for Batteries of High Energy Density."[2] To his surprise, it was already two and a half years old, having been published in June 1980. The four authors, all of whom came from Oxford University, included John Goodenough.

Yoshino would always remember that moment. In the preceding year, he had decided to employ a material called polyacetylene as a battery anode. Polyacetylene had been an unconventional choice for an anode. Yoshino himself referred to it as "daring," largely because it was a nonmetal. It was, in fact, a polymer—that is, a plastic-like material. But unlike all polymers and plastics to date, polyacetylene could conduct electricity. He had become interested in it for a number of reasons, among them the fact that he had been a disciple of Professor Kenichi Fukui of Kyoto University, a corecipient of the 1981 Nobel Prize in Chemistry. In 1979, Fukui coauthored a paper that predicted the existence of materials like conductive polyacetylene.[3] Fukui had been the first Asian to win a Nobel Prize in Chemistry, and the award had been a source of pride for the Japanese people, for the university, and for Yoshino himself. Yoshino was a graduate of Kyoto University and had been taught by pupils of Fukui.

In the beginning, before he had considered it as a battery anode, Yoshino hadn't known what he would do with polyacetylene. As he saw it, the material could be used to replace copper wires on a semiconductor transistor, or in a solar cell. But over time, he grew fascinated by polyacetylene's ability to allow lithium ions to be electrochemically inserted and extracted. Due to this fact, polyacetylene fell into that growing body of knowledge called intercalation chemistry that was being studied by other scientists around the world, including Stanley Whittingham at Exxon Corporation.

That was how he had settled on the idea of a polyacetylene anode. In retrospect, Yoshino would later say that he foresaw it being used in connection with the portable electronic devices that were becoming so popular in Japan. Increasingly, he said, it was becoming clear that devices like the camcorder and the mobile phone would need better batteries. State-of-the-art batteries in 1983 included disposable alkaline batteries, rechargeable lead–acid, or rechargeable nickel–cadmium. But none of those had the high voltage, energy density, or low weight needed for portable electronic devices, he thought. Polyacetylene, however, might offer all those benefits.

In 1982, Yoshino began searching for a cathode material to combine with it. That was when the stress started, according to Yoshino. He tried all kinds of chemical compounds—among them, Whittingham's titanium disulfide. But Yoshino quickly found that titanium disulfide wouldn't work with polyacetylene. He then started delving into a seemingly endless list of other compounds: chromate, carrollite, copper sulfide, vanadium oxide, vanadium sulfide, molybdenum oxide, molybdenum disulfide, vanadium diselenide, iron phosphorus trisulfide, nickel phosphorus trisulfide, and others. None were satisfactory, mainly because they all needed to be paired with a metallic lithium anode, and Yoshino didn't want to use metallic lithium.

That's when he stumbled onto Goodenough's 1980 technical publication. Goodenough's paper was spare—only seven pages. But the information in it was exactly what Yoshino needed. Goodenough had developed a lithium-based cathode that could be used in a nonaqueous battery. It offered a cell voltage of approximately four volts, nearly 60 percent more than that of lithium titanium disulfide. And it had high energy density and good reversibility. Now, he had his cathode.

To be sure, the idea of a rechargeable, nonaqueous battery didn't necessarily appeal to board members at Asahi Chemical. Asahi Chemical was a giant multinational corporation with interests in many areas, including petrochemicals and engineered materials, but batteries were not among them. Truth be told, all efforts to study batteries were considered to be a waste of money by the company's board.[4]

But Yoshino and his colleagues hadn't been told to stop, so their research continued. When the new year began, team members synthesized some lithium cobalt oxide in their lab. They placed the cobalt oxide on aluminum foil and created a cathode, then put polyacetylene on copper foil and used that as an anode. They quickly learned that the prototype battery cell could easily be charged and discharged. "It was the moment that a true secondary battery using polyacetylene in the negative electrode was born," Yoshino wrote thirty years later.[5] This breakthrough went one step beyond Whittingham's battery. Now, lithium ions were being inserted at *both* electrodes. The "rocking chair battery" proposed by Michel Armand a few years earlier was being realized. In short order, Asahi Chemical applied for a patent on a lithium battery using a polyacetylene anode and lithium cobalt oxide cathode.[6]

In truth, though, the journey was far from finished. Other issues would later come up, making the conductive plastic a questionable choice for an anode. Still, a major milestone had been reached. They had created a rechargeable battery cell offering four volts. They'd created a new type of anode and inserted lithium in its atomic structure. They'd eliminated the need for metallic lithium anode, thus solving the fire problems that had plagued earlier rechargeable lithium batteries. And they now had a rechargeable cell that could offer greater energy density than nickel–cadmium at half the weight. For a company that considered batteries outside its core competency, the achievement was nothing short of astonishing.

Whether the board members at Asahi Chemical knew it or not, history had been made. The world was now one step closer to a rechargeable lithium battery.

Akira Yoshino's path to this moment in history would always be unclear. He was a private man, reticent to talk about his early years. But what was known was that he'd grown up in postwar Japan, in the city of Suita, Osaka Prefecture, in the north central part of the country. Suita was a medium-sized city of the time, with a population of about 78,000, on its way to 120,000 by 1960 and a quarter million by 1970.

Born in 1949, Yoshino was one of four children. By all accounts, his life was ordinary for the time, but that particular time, of course, was hardly ordinary. It involved a great deal of hardship and sacrifice for the Japanese people. No one could avoid it. During World War II, most of the big cities had been destroyed, leaving millions homeless. In 1946, an estimated 47 percent of the population had no roof over their head.[7] Public transportation was virtually nonexistent; trolley cars and buses were gone. Food was scarce; even the "wealthy" struggled to have enough. At first, rice could only be bought on the black market. Prices of other necessities were high; inflation was severe. Annual per capita income in 1946 was $17.[8] For most families, it was impossible to save money. Clothing, too, was difficult to obtain. The fortunate dealt with small, crowded housing, typically unheated. Lucky families owned radios, allowing them to connect to a broader world, and sewing machines, which enabled them to repair the few clothes they had. But for most, the two most vivid postwar memories were of cold and hunger.

By the mid-1950s, some of that hardship had eased a bit, but most families still had little beyond the absolute essentials. Real disposable income was almost nonexistent, but the definition of necessity broadened slightly. Businessmen, especially those with important jobs, had two shirts and two suits—a good one for the office and a bad one for home.[9] Flush toilets also started to appear, much to the excitement of city dwellers. The few families who owned one were the envy of the neighborhood, and friends would inevitably make pilgrimages to view them, even if they weren't yet connected to a sewer line.[10] Washing machines and dryers appeared, but were still only for the wealthy. Family cars, however, remained nonexistent. Whereas American families of that era typically had one or two, Japanese families almost never had one. Most considered them a symbol of a frivolous society, a waste of precious metal.[11]

It was in this postwar economy that young Akira Yoshino grew up. It's not known how much or how little his family had, since his only public pronouncements on the matter are that he was "surrounded by a gentle family" and that he "spent lively boyhood with a constant smile."[12] Various accounts describe him catching beetles and dragonflies among the bamboo and bushes near his home.[13] What is clear, however, is that Yoshino was the benefactor of a strong educational system. Japanese leaders of the day had a powerful desire for postwar recovery and thus modeled their country's economy on the American economy. And, in their eyes, the best path to recovery was to encourage the country's hungry labor force to work hard, make financial sacrifices, educate their children, and bear their burdens with stoicism.

That was the way it was in Yoshino's home. It was an austere and disciplined childhood. He quickly found a place among his school's better students and declared an early interest in science. The defining moment of Yoshino's youth seems to have occurred in fourth grade. The story, later to be told repeatedly in the Japanese press,[14] was that his teacher encouraged him to read a book, *The Chemical History of the Candle*, which had a profound effect. The book, authored by legendary British scientist Michael Faraday in 1848, described the different combustion zones of the candle and explained the meaning of the flame's various colors, apparently spurring an interest in chemistry. Yoshino's experience with the book would become so well known that eager Japanese newspaper reporters sixty years later would actually go back and track down the teacher, who by that time was in her eighties and did not recall it.[15]

The book, however, apparently made a difference for Yoshino. At a young age, his growing proficiency in science inspired him to put nails and hydrochloric acid in his home toilet to see how hydrogen was formed. Later, he read a monthly magazine called *Kids Science*, which taught him how to do basic experiments. He used a tube and lens to build a microscope. He also fashioned a powered wooden boat using rubber bands, a propeller, and a rounded kamaboko board. And he combined zinc with black manganese dioxide powder, poured an electrolyte in it, and built his first battery.[16] All of this happened while he was still in elementary school. By the time he reached high school he was part of the swimming club, but teachers were already recognizing him more for his ability in chemistry.

It was therefore natural for Yoshino to follow that passion when he enrolled in college. In 1966, he began his studies in petrochemistry at Kyoto University, earning a bachelor's degree there in 1970. A master's degree followed in 1972. By the time he finished his master's, he had decided not to move on to a PhD, instead taking a job in private industry with Asahi Chemical Corporation. Founded in 1931, Asahi Chemical was a big company with thousands of employees, and it did business around the world. One of its businesses was the production of Saran Wrap, which involved a partnership with Dow Chemical in the US. It was also starting to delve into engineered materials for the fast-growing semiconductor market. For a new graduate, it was a prestigious place to work. As with so many Japanese men of that era, that job would become Yoshino's life, and he would remain in it until retirement, when he was designated an Honorary Fellow in 2017.

In the lab at Asahi Chemical in 1972, Yoshino launched his long career. By the time he filed for the first of his lithium battery patents, he had already been at the company for eleven years.

The extent to which Asahi Chemical's corporate board recognized Yoshino's early battery work is unclear. Equally unclear is whether the board made any mental connection between that work and the coming of the portable electronics boom that would soon be sweeping Japan. By 1983, Sony Corporation was already preparing to release its first camcorder. And more camcorders were coming. It was also clear that the mobile phone was on its way. Motorola had demonstrated the technology a decade earlier, and its first consumer product was destined to hit the market in 1984. Service providers were already jockeying for position, and in the US the federal government was actually holding a lottery to see which ones would be awarded licenses to serve the lucrative cellular phone market.[17] At the same time, the idea of the portable computer was gaining momentum. In 1983, Sharp introduced a twelve-pound "anyplace, anytime" computer. And at the Comdex computer trade show in Las Vegas in 1984, electronics manufacturers rolled out seventy-five new portable computers, with a few falling into a new category called "lap-held" computers.[18] Clearly, the world of technology was on the verge of a very big change, and many electronics engineers believed they needed a better battery to complement the new electronics. But Asahi Chemical's board took a more insular view of the situation. It simply saw the battery business as being far from the company's core, and the electronics business as being even farther.

Worse, polyacetylene was increasingly being seen as a questionable solution, even by those within Asahi Chemical who were ardent battery supporters. The polyacetylene anode, they said, had many drawbacks. Among them was the fact that it deteriorated after contact with the battery's liquid electrolyte. Moreover, large-scale manufacturing was a big challenge because storage of acetylene in multiple vessels around a plant was considered an explosion hazard. Researchers actually referred to the acetylene vessels as "bombs."[19]

Such problems might have been considered solvable, were it not for the fact that polyacetylene also had one other issue: It was too bulky. At first, team members had looked at the low density of the material and identified it as a benefit because it translated to lighter weight. This, they thought, would be perfect for the portable electronics boom. But they soon realized there was a downside. A low-density polyacetylene anode took up more space than a heavier metal one.

So researchers began considering an alternative to polyacetylene. The alternative was carbon. It was a difficult decision and a complicated one. There were more than a hundred forms of commercial carbon. And no one really knew which one to use, or whether carbon would allow for the intercalation of lithium, the way polyacetylene had.

Ultimately, a decision would be made—a decision that would change the course of technological history. History would later identify Akira Yoshino as the man behind the decision, the lone inventor. The *Mainichi Shimbun*, one of Japan's biggest daily newspapers, would many years later run a headline declaring, "Yoshino-san Nobel Prize in Chemistry: One Person Silently Commercialized Lithium-Ion Battery in Ten Years."[20] And Yoshino would not discourage that idea.[21] But, as is always the case with such major product developments, there was more than one inventor.

Akira Yoshino was by no means alone. There were other battery researchers within Asahi Chemical. Two of those (Takayuki Nakajima and Kenichi Sanechika) reported directly to Yoshino; two others (Syunji Ohuchi and Isao Kuribayashi) were higher in the organization than Yoshino; and another (Ikunari Komatsu) worked on carbon fibers at a separate lab within the company. And although Komatsu did not work on batteries per se, he would, like the others, end up playing a key role in the development of the carbon-based rechargeable lithium battery.

The prevailing media idea that "one person silently commercialized" the battery was inaccurate. They were very much a team. They all cared deeply about the technology, and they all had their own ideas about what would work. But like so many teams in so many areas of corporate life, there would be undercurrents of competition. Even within such small teams, there were competing cliques and factions. Not everyone agreed on the best path to success.

That was the case at Asahi Chemical in 1985. Some team members strongly believed in one vision of the future, while Yoshino believed in another. In the version of events put forward by the other team members, Yoshino was still committed to the polyacetylene anode. He liked its ability to store lithium ions; he liked its light weight; and he especially liked its connection to his alma mater, Kyoto University, as well as to Professor Kenichi Fukui.

The rest of the team, however, saw the limitations of polyacetylene. They believed it wouldn't work, for several reasons. Its energy density was low. Equally important, it reacted badly with liquid electrolytes.

Thus, those team members embarked on a separate research path, which would run in parallel with the polyacetylene efforts. Syunji Ohuchi, who was Yoshino's boss, granted them permission to launch the separate effort, and Yoshino did not object, they said. In their version of the events, Isao Kuribayashi, a company manager charged with developing new business for Asahi Chemical, started looking at carbons. Kuribayashi was, in essence, an in-company entrepreneur. But he was also an accomplished chemist. He had a master's degree in chemical engineering from Hokkaido University and would later go on to earn a PhD from there. Moreover, he had worked on lithium batteries. He was also in touch with the company's Nobeoka Laboratory, where Ikunari Komatsu had been developing a so-called vapor-grown carbon fiber (VGCF). Vapor-grown carbon fibers, also known as "carbon whiskers," were a fine granular material, which, on the atomic level, looked a lot like polyacetylene. Seeing the potential of carbon whiskers, Kuribayashi traveled to the Nobeoka Lab to bring back a small bag of them to Kawasaki for testing. Two of the scientists (Nakajima and Sanechika) then worked on an anode made from carbon whiskers, and then on a full-scale experimental cell. So it was that at the Kawasaki Lab in 1985, Nakajima and Sanechika successfully intercalated lithium into carbon. It turned out to be a historic event. "In many ways, this event should go down in the history of battery technology as the real invention of the lithium-accepting negative electrode and these are the inventors," Kuribayashi later wrote.[22]

In retrospect, their success would have a huge impact on the battery industry, the electronics industry, and the automotive industry. It was the primitive beginning of a power source that was unlike anything on the market at the time.

Even then, however, team members said Yoshino continued to be skeptical about using carbon. "The moment of the birth of the lithium-ion battery was celebrated by Dr. Sanechika, Dr. Ohuchi, Dr. Kuribayashi and me," Nakajima later wrote. "Dr. Yoshino just looked at the evaluation data and still insisted that the negative electrode material candidate should be PA [polyacetylene], and not VGCF [carbon whiskers]."

After some discussion, the research team's members moved to an alternate approach. They decided to build separate C-sized cells—one with polyacetylene as the anode and another with carbon whiskers as the anode—and to present them to customers. Thus, the researchers completed their cells and ventured out to talk to potential users—cell phone makers and a manufacturer of VCRs. "Both types of batteries were presented to the customers," Nakajima said many years later. "And the customers decided the carbon material was overwhelmingly superior. After the customers picked the carbonaceous material, Yoshino finally agreed."

Still, the rechargeable lithium battery was far from completed. As it turned out, carbon whiskers were not the ultimate solution, either. They worked; they stored lithium. But they were impractical. Their cost was exorbitant, and they weren't readily available. Therefore, Syunji Ohuchi suggested that the scientists collect carbon materials from inside and outside the company. He told them to search for any carbons having behavior similar to that of carbon whiskers.[23] Over the next few weeks, the team searched out different types of carbons, and experimented with resins derived from asphalt, crude oil, and coal tar.[24] At some point the lab's director, Masashi Mitsuishi, suggested they consider ground petroleum coke—a soft gray material commonly used in steel manufacturing. Petroleum coke was a great solution for many reasons. It was cheap, available by the ton, and could serve as an intercalation compound for lithium. It wasn't long before the researchers began using petroleum coke to make sample battery anodes.[25]

It was then, the researchers later said, that Akira Yoshino stepped in with greater authority. Seeing the experimental data, the success of the coke anodes, and the customers' preference for carbon, he began searching for coal-based cokes. Ultimately, he located and ordered a two-hundred-liter fiber drum of petroleum coke from a supplier. From that point forward, the team would be focused on a petroleum coke anode.

Aside from a few people inside Asahi Chemical during the 1980s, no one knows how the first carbon-based lithium rechargeable battery was created, nor who was really responsible. What is known is that there's disagreement on who did what.

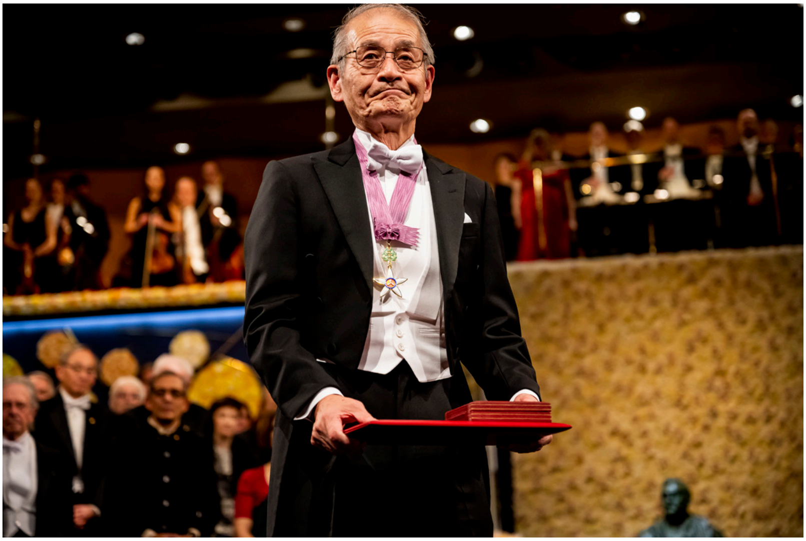
In his book, *Lithium-Ion Batteries Open Doors to the Future: Hidden Stories by the Inventor*, Yoshino made it clear that he was the force behind it all. Yoshino wrote that he recognized the limitations of polyacetylene and therefore launched a search for other materials. Ultimately, he said, he was the one who settled on carbon whiskers, obtaining a sample from one of the company's other labs. And he liked its potential for use in a battery. "Immediately after the New Year of 1985, I charged the battery for the first time that was made in the combination of negative, VGCF, and positive, lithium-cobalt-oxide," he later wrote. "In this year, the carbon/lithium-cobalt-oxide battery was born."[26]

In his book, Yoshino did not mention the role of any other scientists in that birth. Two, however, were cited in key patents.[27] He later acknowledged that those two colleagues—Nakajima and Sanechika—played a role.

But the decision to move to petroleum coke, he said, was solely his. When he later determined that carbon whiskers would not be practical, he said, he began searching for other types of carbons. "What I did was to collect the information on carbons from manufacturers, such as catalogues, X-ray analysis, density, property tables including coefficient of thermal expansion, and other data, then to compare VGCF properties among them," he wrote.[28] In all, he said, he evaluated more than one hundred types of carbon without success, before fortuitously stumbling upon a new property table from a supplier. "Luckily, I happened to find a group of cokes that were used for a specific use and these had properties similar to VGCF," he wrote.[29] It was then that he approached the manufacturer and obtained a two-hundred-liter drum of petroleum coke, he later wrote.

It would later be impossible to say whose version of events was closer to the truth. During the years after Asahi Chemical's crowning achievement, most of the scientists moved on. Two retired early, one was transferred to a different part of the company, another left the company altogether, and another passed away. Thus, the remaining scientist was Yoshino, who would, for better or worse, tell the tale his own way. And Asahi Chemical would support his version. It would not advocate for those who had left its employ.

So it was that in the end, it became a Yoshino story. History would record it as Yoshino's anode. He had been there at the beginning and had stayed with the company. He'd been a loyal soldier, as well as a codeveloper. Gradually, his designation as *the* inventor would be cemented at technical conferences and later in his book. Whether others had been involved—indeed, whether they had actually



Akira Yoshino was awarded the 2019 Nobel Prize in Chemistry for the role he played in the development of the carbon anode. (© NOBEL MEDIA. PHOTO BY A. MAHMOUD.)

been the inventors—was not the issue. Yoshino had remained. He had persevered. And, ultimately, the world would recognize him as the sole creator of the soft carbon anode.

Whoever was responsible, the battery was now beginning to take shape. It consisted of a petroleum coke anode and Goodenough's cobalt oxide cathode. It used a porous separator and a liquid electrolyte made from lithium salts and a propylene carbonate–based solvent (PC). And it offered the high voltage, high energy density, and reversibility that engineers had dreamed of for decades. It also bore an uncanny resemblance to the batteries that would proliferate around the world for thirty years to come. It was, quite simply, the battery of the future.

At this point, Asahi's management began to reconsider its position on batteries. To be sure, the company's board members didn't view rechargeable lithium batteries as a potential windfall, but they no longer viewed them as a waste of research money, either. Isao Kuribayashi was in some ways the battery's sponsor within management, and he was an ardent believer in its potential. He viewed it as a suitable contender for use in camcorders, mobile phones, and portable computers.

Still, he knew that Asahi was a long way from having a commercial battery. The researchers were able to produce a C-sized cell that had the look and feel of a commercial product, but they were doing it at a rate of just one cell per week. To be competitive, they would need to produce millions. Thus, Kuribayashi's vision was to develop a pilot production plant, a site for small-scale production. He wanted to have a semiautomated facility in the beginning. Eventually, his goal was to have a plant capable of producing relatively small production quantities—perhaps a few thousand cells per week. Kuribayashi understood, however, that Asahi Chemical had no expertise in such matters. Taking the next step would require that he find people who were experienced, not only in batteries but in automated production.

So it was that in the final months of 1985, Kuribayashi began canvassing US-based battery machine producers and small battery companies. He needed someone who could take Asahi's research and turn it into a production battery. And he wanted the battery to get an exemption from the US Department of Transportation regulation that prevented lithium-based batteries from being taken aboard airplanes.

He had good reason for searching for a US partner. In Japan in 1986, Kuribayashi couldn't simply ring up a local tool and die shop and ask them to make hundreds of C-sized batteries. Few companies had the expertise for such work. Worse, if Asahi called someone in Japan, *anyone* in Japan, the word would inevitably spread, and every electronics and battery manufacturer in the country would know that Asahi Chemical was onto something big.

So Kuribayashi intuitively understood that he needed someone smart and discreet—someone with specific technical knowledge, yet someone who was small enough to have very few connections to the world market. And more than anything else, he needed someone outside Japan.

They arrived unannounced. Isao Kuribayashi and Akira Yoshino knew the proprietor of the company they were visiting, but they had no appointment. It didn't matter, however. The company, Battery Engineering Inc., was a small shop and would require no advance notice. There were no layers of management between them and the person they came to see. So the two of them showed up, not knowing what kind of reception they would get, and not knowing if this tiny company would be willing and able to help.

It wasn't their first stop. They had flown first to Rochester, New York, where they'd met with a company called Alliance Automation Systems. There they had talked about machinery for their planned pilot production plant. Then they had flown to Boston, where they had stayed in a hotel and taken a taxi to Battery Engineering Inc. in the Hyde Park area of the city.

It was not the type of facility to inspire great confidence, nor the sort that would attract visitors from around the world. Battery Engineering was housed in a converted truck garage next door to an auto body shop. Its bare walls were made of concrete block. The floors were unfinished and the place was, in general, a bit grimy. It had two big garage doors and a loading dock in back, where the company's founder, Nikola Marincic, had constructed a dry room—a place of low humidity for working with fire-prone battery compounds. In the battery assembly area, it had a few machines for winding and sealing of finished products. The machines had been purchased secondhand and then personally refurbished by Marincic.

Marincic knew the Japanese visitors from a meeting they'd had at a battery seminar a few months earlier. He'd been highly recommended to them by their US advisor, Dr. Per Bro in Santa Fe, New Mexico. Bro was a consultant who had spent a lifetime with Mallory Battery and Duracell. He knew the world's best battery people, and he considered Marincic to be among them. Marincic, he said, was that rarest of scientists, a man who understood batteries from a theoretical standpoint but also knew how to produce them in a factory. He had earned his PhD in chemical engineering from the University of Zagreb in Yugoslavia and had served in battery development for GTE Corporation and Duracell Inc., where he had earned a reputation as a practical man who could build unusual batteries. As a consultant, he had created batteries for fighter jets at Hughes Aircraft, for pacemakers in the medical industry, for downhole drilling applications in oil fields, and for US government missile silos. Somehow, companies with complex battery problems were always able to find Marincic and his little shop, and those companies had made Battery Engineering into a thriving operation. Moreover, Marincic was assisted by four bright young PhDs and by a group of talented assemblers who knew how to use his machinery.

For Kuribayashi and Yoshino, it didn't take long to conclude that Marincic could help. In Japan, there were no specialty manufacturers with capabilities like these.

Nikola Marincic of Battery Engineering Inc. built the first preproduction rechargeable lithium cells at a converted truck garage in Boston, Massachusetts. (PHOTO COURTESY OF LIDIJA ORTLOFF.)

And even if such shops had existed in Japan, Asahi Chemical would have been unlikely to use them. Secrecy was key here, and no shops in Japan could guarantee that. During the 1980s in Japan, companies in the battery industry were all part of the same *keiretsu*—a conglomeration of enterprises with cross-shareholdings and interlocking interests. And if one company in the keiretsu knew another's business, then it was a good bet that they all knew. Therefore, building these new batteries in Japan would be as good as telling Matsushita, Sony, or Sanyo that Asahi Chemical was coming out with a new battery chemistry.

Kuribayashi and Yoshino were now believers in the potential of their new battery. Both were strongly motivated to keep the project moving before the company's board changed its mind. They provided a few more battery details and explained that they wanted a finished product, like something a person might buy in a grocery store. "They said, 'If you want to build the batteries, then don't ask any more questions,'" Marincic recalled years later. "They didn't tell me who sent them and I didn't want to ask."

Marincic did, however, discuss money. "I said, 'It's going to cost you,'" he recalled later. He quoted a price of $30,000 for two hundred preproduction cells, to be delivered in two weeks. The finished batteries, he said, would be working products. More, he believed these batteries would be capable of getting clearance from the US Department of Transportation, so they could be taken back to Japan on an airplane. Because Marincic dealt every day with dangerous materials, he knew what could be legally transported and what couldn't. He understood from experience that lithium primary batteries, which had been available for nearly two decades, were considered a fire risk and therefore not allowed on commercial flights. But this new battery used no active lithium—only a cobalt oxide cathode and a petroleum coke anode. The lithium was present only in the form of ions in the liquid electrolyte. The batteries were, in his estimation, not real lithium batteries and, therefore, not dangerous. When Marincic finished his explanation, the visitors agreed to his price and departed for a hotel in Boston.

A few weeks later, they were back. This time the visitors were Kuribayashi and Takayuki Nakajima, both of whom planned to watch every step in the production process. With them, the scientists brought three jars. The jars contained a black slurry, a gray slurry, and a liquid. One was marked "positive," another was "negative," and the third, which contained a liquid electrolyte, had no markings.

Marincic knew the contents of the jars, but he did not share his knowledge with Battery Engineering's researchers. "He tried to tell us this was a navy contract, but we just looked at him and laughed," recalled Walter van Schalkwijk, a PhD-level researcher for the company at the time.

Still, the work was shrouded in secrecy. The Japanese visitors knew the weights of all the jars coming in and wanted to know the weights going out as well. They wanted every scrap of material accounted for, so that no one could keep bits of excess material and then reverse-engineer their battery.

For Marincic, the task was not a terribly difficult one. His visitors, in essence, wanted "jelly roll" batteries. Jelly roll batteries were so named because they were wound like a piece of pastry. Each electrode—a narrow band measuring as much as a yard long—would be laid flat, one atop the other. A separator would then be placed in between them. Using hand-winding equipment, the three parts would then be tightly wrapped into a cylindrical shape (like a jelly roll) and placed in a stainless steel can with a stainless steel cover. Battery Engineering would then use its laboratory tools to evacuate gas from the cell can, inject the liquid electrolyte, and hermetically close the lids. The result was a far cry from what passed for a battery in a lab. Lab batteries could be as simple as two electrodes in a couple of glass beakers filled with electrolyte. What Marincic built was a metal cylinder, more like what a consumer might buy at a grocery store.

Marincic suspected that his visitors owned most of the same machinery—the same winding and sealing equipment. But he also understood that they lacked the assembly experience necessary to create a battery. "Equipment is one thing," he said. "But the man who operates the equipment is another matter. And these particular people—I could tell, they were not shop people."

Every day after the deal was struck, Kuribayashi and Nakajima took a cab from their downtown hotel back to Hyde Park to quietly watch the construction of their batteries. Throughout the workdays, they hovered over Battery Engineering's researchers, learning every step in the manufacturing process. Over two weeks the scientists said little. When the job was finished, one pulled out a checkbook. "They wrote me a check in my office and I handed them a package of batteries," Marincic later said. "And that was it." Then, the visitors departed as quietly as they'd arrived. Years later, Kuribayashi would still have sample batteries and would publish photos of them in his book.[30]

In June, the Asahi scientists took the box of batteries to an independent laboratory for testing. The lab, NTS Inc., did every imaginable kind of battery test—high-temperature tests, drop tests, crush tests, short circuit tests, pressure tests, penetration tests, overcharge tests, and vibration tests. In a report dated July 1, 1986, NTS engineers concluded that the batteries had passed all of them.[31] Shortly afterward, Kuribayashi applied to the US Department of Transportation for the batteries to be permitted to be brought aboard commercial aircraft. In a letter, he specifically asked that they not be categorized as metallic lithium batteries. In a response dated October 21, 1986, his request was granted.[32] In it, the DOT wrote that his products "are not lithium cells and batteries."

Now, it was official. They had a working battery that produced four volts, offered high energy density, and was rechargeable. More, it was not a science project; it was a finished product. And it had clearance from the US DOT. It could henceforth serve in any application—a computer, phone, or camcorder—aboard a commercial aircraft.

At this point, Kuribayashi began to think about volume production. He arranged for automation machinery to be placed in Asahi's Kawasaki Laboratory. And he began considering development of test facilities. Now, there was good reason for Kuribayashi and Nakajima to believe that their battery would soon be a commercial product.

So by late 1986, the debut of the commercial rechargeable lithium battery appeared to be on the horizon. And, oddly enough, the first preproduction version of it had been completed in a converted truck garage in Boston, Massachusetts.

For decades, however, no one would know about the construction of the batteries at Battery Engineering. At the behest of Asahi Chemical, Marincic told no one. Even van Schalkwijk, who worked for two weeks on the project, didn't know that he'd participated in a historic event. He finally learned of it in 2020 when Brian Barnett, a battery consultant with an encyclopedic knowledge of lithium-ion history, pointed out a passage in Kuribayashi's book. "I had an inkling of what we were working on," van Schalkwijk said thirty-four years later. "But I had always assumed the first [rechargeable lithium] batteries were built in a Japanese lab by a Japanese corporation, not by Battery Engineering."

Thirty years later, it would be impossible to determine when and how the Sony Corporation had begun considering the development of its own rechargeable lithium battery. By the 1980s, Sony was already a mammoth, multilayered company. In retrospect, its public relations machinery would publish neatly scrubbed and sanitized versions of the battery's birth. But the real story would remain unclear. Yoshio Nishi, the scientist most responsible for the Sony battery, would on different occasions say he had begun working on it in 1985, 1986, or 1987.[33] Nishi, a Sony lifer, had started his career in zinc–air batteries two decades earlier, straight out of school from Keio University in Tokyo. He had spent eight years in batteries before Sony moved him "against his will" in 1974 to the development of electroacoustic materials for loudspeakers and headphones.[34] That assignment would last twelve years. Nishi would later declare, however, that the assignment had turned out to be fortuitous because it exposed him to the science of many new materials, particularly carbon-based compounds.

His path to the rechargeable lithium battery would be a circuitous one. It started when Sony set a goal to build a better handheld camcorder. To build it, Sony engineers believed they needed to start with a better battery. A better battery, they reasoned, would enable the camcorder to be small and lighter and would give it more run time between charges.

For Sony, it was a project of utmost importance. As big and well-established as Sony had become, it still saw itself as an innovator, a market disruptor, and this battery was going to be one of its great disruptions. Such thinking was part of Sony's corporate DNA. The company had an amazing history, having risen from the ashes of post–World War II Japan to become one of the world's best-known electronics makers. By 1985, it was a global leader in many areas, including audio recording, video recording, optical storage, television, photography, and computing.

Its rise was astonishing, especially considering that thirty-nine years earlier its first innovation had been an electric rice cooker and its second, a crude toaster oven.[35] Back then, the company had done whatever it needed to do in the decimated postwar economy, including selling sweetened miso soup in order to make ends meet. But it had been an innovator from the beginning. In the 1950s and '60s, it had built radios and tape recorders; in the '60s and '70s, it manufactured televisions and semiconductors. By the 1980s, it was still on the leading edge of technology. It introduced a portable typewriter called the Typecorder, a microcomputer known as the SMC-70, and the Sony Walkman, which in itself represented a revolution to music lovers around the world. And now, its newest innovation was going to be a handheld camcorder called the Handycam.

The Handycam was to be a palm-sized video camera, and while Sony executives had reconciled themselves to the fact that early versions of it would have to use existing battery chemistries, they dearly wanted to move beyond the status quo, which was nickel–cadmium. Nickel–cadmium, they insisted, was not a viable long-term solution. It was rechargeable, yes, but its energy density was mediocre. Early versions of Sony's eight-millimeter camera used five big nickel–cadmium batteries, and those five batteries needed to be recharged frequently.

The alternative, of course, was to employ "primary" batteries—that is, disposable cells that could not be recharged. Sony was very familiar with primary cells. The company had started using them in 1955 on its TR-55 transistor radio. But Sony executives intuitively understood that disposable batteries would not be a long-term solution. By 1986, Sony already had two decades of experience with products ranging from battery-powered boomboxes to tape players to portable music devices, like the Walkman. Its executives knew the advantages and disadvantages of disposable cells in their various sizes—AA, AAA, 9V, and even the so-called chewing gum batteries that could be purchased from outdoor public dispensers. They knew that a big camcorder would require bulky packs of such batteries and, worse, that those bulky packs would soon end up in landfills. By 1986, the average American household (Americans were the biggest battery consumers) was already throwing out thirty-four used batteries per year,[36] and camcorders would only make that problem worse. Moreover, disposable cells employed trace amounts of mercury, a toxic element, adding to the environmental problem.

To some degree, rechargeable batteries offered hope. They drastically reduced the disposal issue. But strong candidates were nonexistent. Sony essentially dismissed the lead–acid *yokan* battery, so named because it was about the size of the sugary, block-shaped Japanese dessert called the yokan.[37] Yokan batteries were far too heavy because they had low energy density. Thus, nickel–cadmium was considered the best of the rechargeable lot, but that, too, was now frowned upon because of its low energy density and toxicity.

So it was that rechargeable lithium came to be viewed as a savior. Still, the chronology of Sony's actions with regard to lithium batteries would always remain vague. Its effort started before 1985 with its giant American partner, Union Carbide Corporation. Up to that point, Sony had depended upon an arrangement with Union Carbide for much of its battery development. The two companies had a decade-old partnership, known as Sony-Eveready, which called for Union Carbide to do the battery development, while Sony performed the manufacturing. But while Sony-Eveready was quietly working on a rechargeable lithium battery, its efforts apparently yielded little. Sony executives would later claim that in the last few years of the partnership, they had pestered Union Carbide to accelerate its rechargeable lithium battery development, but the American company had "dragged its heels."[38]

But on December 3, 1984, an event occurred that would make the pestering irrelevant. That was when a Union Carbide plant in Bhopal, India, accidently released toxic gas into the air, causing the worst industrial disaster in human history. About thirty-seven hundred people died as a direct result, with thousands more dying of illness in the months and years afterward. At least half a million people were also sickened or injured. In the aftermath of the Bhopal incident, as Union Carbide struggled with all of the related legal and financial ramifications, the American company made the difficult decision to divest itself of its consumer businesses, which included batteries. The decision sent a wave of panic through Sony's upper management. Sony executives flew to the US along with the company's legal team; they did not want control of Sony-Eveready falling into the hands of a third party. In March 1986, after days of bargaining, Sony's lawyers successfully negotiated a purchase of Union Carbide's shares of Sony-Eveready. Sony then created a new business called Sony-Energytec Inc.

At this point, even inside Sony corporate headquarters, no one was sure how far the dissolved Sony-Eveready unit had come in its efforts to create a rechargeable lithium battery. Sony-Eveready was, to some degree, a semi-independent company within Sony, and its research results were a little-known entity. What was known is that Sony-Eveready had worked on a rechargeable battery and had begun installing some manufacturing equipment. But executives at corporate headquarters weren't confident in the technology. Therefore, they now decided to take control of the project by putting their best people in charge.

And the best of those was Yoshio Nishi. Nishi was therefore transplanted from the Sony Central Research Laboratory to the new Sony-Energytec unit. There, he would take the reins of the lithium battery project.

Here, however, Nishi and his colleagues now faced the need for a crash course in lithium electrochemistry. Rechargeable lithium battery chemistry was still a new discipline, not yet well understood in Japan, and Nishi had little or no experience with it. Worse, Sony now had an unexpected competitor. Although the company's executives may not have known it yet, Asahi Chemical was far along in its effort to create a rechargeable lithium battery. By late 1986, Asahi already had a boxful of C-sized wound cylindrical cells. And it's unlikely that Sony had anything comparable. What it did have was a new business unit, a new team, and a battery of unknown value.

Whether Sony knew it or not, however, it was about to get a lesson in rechargeable lithium battery chemistry. And the lesson would come from a most unexpected source.

The question of why Asahi Chemical decided to show its battery to Sony Corporation would never be satisfactorily answered. The possibilities were many: that Asahi Chemical wanted to supply a battery for Sony's camcorders; that it expected to play the role of material supplier; that it expected to launch a joint battery operation; that it planned to license its patented technology to Sony. Most likely, however, the driving forces were timidity and confusion. Asahi Chemical was exploring uncharted territory. And it wanted the help of a big brother

Whatever the reasons, Asahi Chemical executives decided to meet with Sony on January 21, 1987.[39] At that point, Asahi believed it was far ahead of Sony. It had already built cylindrical cells, was installing preproduction machinery, and had received permission from the US DOT to transport its batteries on commercial aircraft. Therefore, when executives from both companies gathered at a Sony facility on that January day, Asahi took measures to protect its confidentiality. Everyone signed nondisclosure agreements, forbidding them from talking publicly or privately about the matter. Isao Kuribayashi then made a brief presentation and rolled out one of Asahi's prized possessions: a single, C-sized battery cell. He handed it over to two Sony executives, Minoru Morio and Katsutoshi Amano, for examination.[40]

That meeting, however, was only the beginning of the discussions. On March 19, 1987,[41] high-level executives from Sony and Sony-Energytec traveled to Asahi Chemical's headquarters in Tokyo to meet again. This time, they asked about Asahi Chemical's plans for the battery. Then they floated the possibility of Sony–Asahi joint venture. Still, they weren't finished. On April 5, Sony executives made contact again, this time requesting details of the battery's chemistry.[42]

To be sure, Asahi knew it wasn't ready for a joint venture. It feared that Sony would quickly take control of it. Nor was it ready to divulge its chemistry. In the chemical industry, that just wasn't done. But the two companies did reach an agreement on formation of a "joint work team," which would allow Sony engineers to operate freely in Asahi's labs and vice versa.[43] The agreement even made allowances for company ID cards to be recognized at each other's security gates. The idea was for the two companies to develop a battery for use in a Sony camcorder. Kuribayashi later wrote that he hoped that Sony would buy Asahi's lithium batteries in large quantities.[44] Sony had great brand recognition worldwide, he said, and he liked the idea that it could be Asahi's first battery customer.

But while Sony teamed with Asahi, it quietly stepped up its own effort to develop a rechargeable lithium battery in house. In July 1987 (six months after the two companies first met), Sony made an official public announcement that its quest for the "development, manufacture, and sales of the lithium rechargeable battery was underway."[45] Keizaburo Tozawa, who had served as chairman of Sony-Eveready, spearheaded the project at the upper management level. Left unspoken by Sony was the issue of what it had been doing in the fifteen months between the formation of Sony-Energytec and the launch of this new project. Even inside the company, few knew how much, or how little, the company had accomplished in pursuit of its quest.

At this point, however, there was no question about Sony's intention nor its dedication to the new task. Tozawa announced that he was assigning six internal teams to the task of evaluating different lithium chemistries. The six-team technique, he said, had been learned from the Japanese Navy.[46] When the navy wanted to hit a target with its guns, it aimed three guns at a single site, thus increasing the chances the object would be struck. That was the idea here: six guns, one battery.

Ultimately, the six-gun technique would work, at least in Sony's telling of the story. The company wrote that it engaged in a methodical approach, one in which lithium chemistries were evaluated and eliminated, one by one, in monthly meetings. "The team was going through the process of trial and error in search for the dream battery," the company wrote. "Finally, one of the research teams began rejoicing; 'We got it!'"[47]

Indeed, they had it. Whether the chemistry had been a product of the defunct Sony-Eveready unit, or the new Sony-Energytec unit, or whether it stemmed from Sony's work with Asahi Chemical, no one would say. Clearly, Sony-Eveready had been working on a battery before it was dissolved. Operating as a somewhat independent entity, it had created *something*. And clearly, the new Sony-Energytec unit had been working on a rechargeable lithium battery chemistry. Moreover, it's almost a certainty that Sony had seen Asahi Chemical's patents prior to the meeting on January 21, 1987. Asahi's first Japanese patent had been filed on May 9, 1985, and had become public in late 1986, months before the meeting. And, given the fact that virtually everyone in the battery business checked for competing patents on a regular basis, it's unlikely that Sony could have missed something so obvious.

Still, Sony did not divulge its progress or its knowledge to anyone outside the company before or after that day. Thus, the only known entity was Asahi Chemical's work. It had shown its battery to Sony, teamed with Sony engineers, and filed for a patent that was now public.

Eventually, Sony's first chemistry would be virtually identical to the one that Asahi Chemical had shown in January of 1987. It would use a cobalt oxide cathode and a soft carbon anode. In retrospect, there would naturally be questions about its origin. Still, no one could say for sure which company was first. "What we can say is that it wasn't a case of Nishi meeting with Asahi, and a light bulb going off, and Sony saying, 'We've got to get into this,'" said consultant and historian Brian Barnett thirty year later. "That definitely wasn't the case."

But the question of how the two companies would end up with identical chemistries would always linger. In its history, Sony wrote that its initial cells used "a special ionic lithium alloy called lithium cobalt oxide for the positive pole and carbon material for the negative pole." But it would forever claim that the battery's chemistry had been developed completely in house. "The selection of the materials for the poles and electrolyte solution of this powerful battery was the result of endless tests conducted by the project members," it added. "For example, there were various types of carbon compounds that could have been used for the negative pole, which would affect the battery's performance. The engineers in charge of materials development searched for a better material in order to find new carbon compounds."[48]

So it was that both companies would later claim that they'd been first, and neither would acknowledge the other. In its corporate history, Sony would not mention Asahi Chemical. And in his 2016 technical paper "The Dawn of Lithium-Ion Batteries," Yoshio Nishi would not credit Asahi or Akira Yoshino.[49] It was as if they didn't exist.

Similarly, Akira Yoshino would manage to write an eighteen-thousand-word book about his role in the creation of the rechargeable lithium battery without mentioning the Sony name.[50] Moreover, in his technical paper "The Birth of the Lithium-Ion Battery," he would acknowledge Sony only once. The question of who did it first, therefore, would never be satisfactorily resolved. Both companies would later say they had developed the chemistry, but neither would point a finger at the other and cry foul. The closest such statement came from Kuribayashi, who diligently chronicled the important dates in his small book *A Nameless Battery with Untold Stories*. He would write that "as a statement of historical fact," Asahi had handed "a nameless cell" to Sony at a meeting on January 21, 1987.[51] He stopped short, however, of directly saying that Sony had employed Asahi's chemistry.

To those outside Japan, the whole affair seemed strange. There was a silent bitterness, but no legal action. Westerners in general viewed the Japanese as fiercely competitive, but only against companies outside Japan. Most believed that Japanese corporations were polite on the domestic front, regularly cooperating with one another rather than competing. But that couldn't have been further from the truth. Japanese companies competed, not only against Americans and Europeans; they competed ruthlessly against each other. They borrowed from one another freely, seldom giving credit. They cut prices and exploited all possible competitive advantages. Their competition within their own domestic market was intense and relentless, Darwinian in a way, and many companies were driven to bankruptcy in the process. The oft repeated example of this corporate Darwinism was the story of Honda Motor Company and the rise of the motorcycle. Honda had been the second largest of fifty motorcycle manufacturers in Japan in the mid-1950s. But through aggressive innovation and fierce price-cutting, it drove almost everyone else from the market. By 1960, only thirty companies remained; by 1965, there were only eight; and by 1969, four, including Honda.[52] In this winnowing-out process, the market's biggest manufacturer, Tohatsu Corporation, had been driven into bankruptcy. Moreover, such behavior was not unusual. Japanese companies competed with everyone as if they were in the midst of an economic war.

Therefore, the question of who developed the first rechargeable lithium battery chemistry was not one of importance in Japan, at least not from a business standpoint. Scientists could argue about who created what, but the job of a Japanese business was, first and foremost, to build market share and defeat competitors.

Still, over time, the relationship between the two companies would sour. Friction between them would long be recognized within the battery industry. To some degree, that friction would even spill over into the Japanese press.[53] But from a practical and legal perspective, it would never matter. Sony's engineering work would extend far beyond the original chemistry—so far that the debate over who was first would eventually be lost to history.

By most accounts, Sony did the engineering work brilliantly. Nishi, who headed the effort, was a talented engineer who by that time had spent two decades learning about materials and manufacturing. After arriving at Sony in 1966, he had risen through the ranks of the company and had built a reputation for understanding the application of new materials. Under him, the company's engineers worked with a wide variety of suppliers to develop the battery's key parts. They teamed with Kureha Corporation on the anode and on binders, Nippon Chemical

Industrial Company on the cathode, Tomiyama Chemical Industries on the electrolyte, Tonen Chemical on the separator, and Lonza Group of Switzerland on the conductive additives. Nishi led briefings between Sony and its suppliers, shared confidential information on the battery's development, and encouraged the creation of a shared team atmosphere in which suppliers were a key part of the effort. Finally, he and his team labored over the development of a process for making the cathode powder in large volumes in house, on figuring out the optimum heat treatment temperature for petroleum coke, and on creating automated machinery to build the batteries at large scale.

The company's work on the battery chemistry was incredibly labor intensive. And, like most such efforts, it couldn't be attributed to the genius of a single scientist or project leader. At Sony, there were many contributors: Kazunori Ozawa, Shigeru Oishi, Masaaki Yokokawa, Toru Nagara, Keizaburo Tozawa, and dozens of others. Their work would go on to earn numerous scientific awards in Japan, including the Tanahashi Prize and the Ohkouchi Memorial Prize.

To be sure, however, their work wasn't always a *eureka!* type of effort. It wasn't the type of work that would inspire flowery press accounts. Rather, it was a quiet, detailed, grind-it-out mixture of science and engineering, without which Sony would never have had a successful product. Much of it was later attributed to Sony's in-house knowledge, especially in thin film coatings and ceramic processing, accumulated over decades of research in the development of magnetic audiotapes and videotapes.[54] But the truth was probably much simpler—it was a gritty engineering effort turned in by a big, well-managed team.

But the biggest difference between Sony's effort and that of Asahi Chemical was Sony's sense of urgency. Sony knew what it wanted and seized the moment. It made the lithium battery a corporate priority.[55] Requests were quickly approved by management and the number of lab instruments was doubled, as was the quantity of raw materials. As a result, every step in the development process was streamlined. When an instrument broke down, another became quickly available.[56] When raw materials for electrodes or electrolytes ran low, there were no ordering or delivery snafus. At the same time, Tozawa's six-gun approach assured that there were always multiple ideas running in parallel within the organization, competing against one another. When one was determined to be a winner, the others were quickly abandoned and the engineering talent reallocated.

As the technology evolved into a real product, Sony maintained its commitment to a chemistry that was similar to the one that Asahi Chemical had demonstrated in January 1987. The anode would be petroleum coke; the cathode, lithium cobalt oxide. But as Nishi saw it, there was much more to it. The chemistry wasn't finished.

"The charging voltage of the cell was 4.1 volts and it had an energy density of 80 watt-hours per kilogram, considerably higher than the nickel-metal-hydride or nickel-cadmium cells at the time," he wrote later. "However, we were not completely satisfied."[57]

Satisfied or not, however, the world would soon have a commercial rechargeable lithium battery.

While Sony was closing in on a commercial version of the rechargeable lithium battery, Asahi Chemical was still trying to figure out what to do. Whereas Sony was decisive and driven by a sense of urgency, Asahi Chemical was timid.

The company's conservative reaction trickled down from the highest level—the board of directors. Isao Kuribayashi recognized it from the beginning. He saw that certain members of the board of directors had been hesitant about getting too deep into the battery business. They had accused the battery researchers of wasting money; they had complained that batteries were not Asahi's core business; they had worried that no one at Asahi had related business experience; and they had doubted all the projections and forecasts for the battery's success.

Still, Kuribayashi forged ahead. By 1988, Sony had already requested that Asahi begin sample battery production. Even though it was developing its own battery, it still wanted Asahi to serve as a supplier. At the same time, Kuribayashi had also begun exploring a relationship with Varta AG, a German battery manufacturer. He wanted Varta as a partner, so he worked with an independent lab in Germany to provide evaluations of Asahi's battery to Varta engineers. Then he supplied components—anodes, cathodes, electrolyte, separators, and cans and lids—so that the Varta engineers could build the battery themselves.

Varta engineers examined the battery. They compared it to nickel–metal hydride and nickel–cadmium cells and liked what they saw. On October 3, 1988, they sent a letter of intent, asking about the possibility of a joint venture.[58] For Kuribayashi, the Varta proposal seemed a logical solution to the objections raised by Asahi's board. Here was an experienced battery maker, nearly a century old, proposing to build Asahi's new battery on its production lines. It *wanted* the lithium rechargeable battery. Moreover, Kuribayashi had also arranged for a customer: Sony, one of the biggest electronics manufacturers in the world, was waiting for sample cells.

Still, the Asahi board balked. Several members complained there was no comparable business scheme, no baseline for them to make an assessment. There was insufficient information, no volume forecasts, they said, except for the case studies provided by Kuribayashi, who had no prior battery experience.[59] Moreover, they didn't like the idea of an arrangement with a German battery company. Why not a Japanese company? They asked. Or even an American company? In fact, they were succumbing to one of the most powerful corporate forces in Japan—fear of failure. In their eyes, there was much to lose and little to gain. If they did nothing, they would lose no status. But if they moved boldly and failed, that was another matter. Failure meant shame.

In the end, their fears prevailed. "They were too conservative to enter into a new business area" where they had no experience, Kuribayashi would later write.[60] Quickly, the Varta joint venture idea "went up in smoke."

It was a moment of great frustration for Kuribayashi. He later wrote that he had a "sinking feeling" and was "struggling with his sense of belonging to Asahi Chemical."[61] He believed that because the majority of the company's board was nontechnical, it didn't fully understand the opportunity. In truth, however, the decision had been born of the very qualities that made so many Japanese companies great. It was conservative and consensus driven. Many of the board members simply didn't understand, and dared not enter a market they couldn't fully comprehend.

By this time, Kuribayashi and others at Asahi Chemical had guessed that Sony was probably taking the lead in rechargeable lithium battery development. Although no one knew how far Sony had come, they all recognized its commitment to the technology. They knew that Sony felt a sense of urgency, and Asahi Chemical did not.

Thus, 1988 would come and go, and still Asahi Chemical would have no production battery.

By 1989, the lithium rechargeable battery was on its way toward commercial production, and there was no doubt who would produce it first. Sony was firmly in the lead at this point, although there were some minor issues that still needed to be cleared up.

The first issue was patents. The lithium cobalt oxide cathode hadn't been developed by Sony, nor by Asahi Chemical. It had been the product of the University of Oxford and, more specifically, John Goodenough and Koichi Mizushima. The patents were owned by the UK's Harwell Laboratory near Oxford. As much as Asahi Chemical and Sony wanted to find a way around those patents (Sony, in particular, did discuss it), it wasn't going to happen. Lithium cobalt oxide was owned by the Harwell Lab. Thus, as Sony would later write in its corporate history, "patents had to be obtained for the carbon compounds and the methods used to create the lithium-ion alloy."[62]

So it was that in 1989, researchers at the Atomic Energy Research Establishment (AERE) in Harwell, England, received an unexpected call from Sony, wanting to discuss a licensing arrangement for one of its patents. The call surprised everyone at the Harwell Lab; AERE had many patents, and at first the researchers couldn't imagine which patent had spurred the interest. Soon, they were amazed to learn that Sony was citing an eight-year-old patent titled "Electrochemical Cell with New Fast-Ion Conductors."[63] Sony wanted to employ the patented technology, although it didn't reveal what it intended to do with it. Moreover, it was willing to pay royalties.

The AERE researchers scratched their heads. They knew of no one—anywhere—who intended to build a rechargeable lithium battery. Moreover, in the UK, Goodenough's patent had seemed more like a curiosity, a battery idea that might still be many years from fruition. "It wasn't clear to us what the market was going to be, or how big it would be," Bill Macklin, an AERE scientist at the time, said many years later.

AERE scientists were so perplexed by the call that some discussed, rather awkwardly, whether it was even appropriate to sell technology from a UK-based nuclear laboratory to the Japanese. Those who had lived through World War II admitted to feeling uncomfortable about Sony's perceived ambitions. Although forty years had passed since the end of World War II, there was still a vague leeriness toward any request from a former national adversary. That was especially so at a nuclear facility.

Still, logic prevailed. The scientists realized that Japan was not going to start a war with cobalt oxide cathodes. But even after being convinced that Sony's intentions were not sinister, they weren't sure how to handle the negotiations. The lab was staffed largely by scientists, most of whom had no idea how to deal with such business-related requests. Ultimately, they relied on its small staff of business development managers and lawyers, who handled the legal arrangements.

Quite quickly, Sony became a licensee. AERE even structured a joint licensing agreement under which Sony would be in a position to provide sublicenses to other battery manufacturers in Asia who wished to follow suit. If other companies were building lithium batteries, and if they wished to use lithium cobalt oxide, they would have to deal with Sony. In that way, Sony acted as AERE's policeman on the ground in Asia, protecting its patent. Eventually, Sanyo, Panasonic, and possibly as many as twenty-five others became sublicensees over the next decade. The amount of royalties paid to AERE is unclear; most estimates put the licenses at $2 million each, plus 2 percent of sales, but the actual figure is unknown.

Even as Sony laid the legal and technical groundwork for the new battery, however, there remained one more rather obvious issue that needed resolution. Sony executives wanted a name for their new product, one that would distance it from the lithium metal–based batteries of the past. Such batteries had already existed for many years; they'd originally been used as power sources for lighted fishing floats on Japanese boats as early as the 1960s. But they were known to be volatile and fire prone if abused—so much so that the US DOT had passed regulations limiting the amount of lithium that could be present in a battery cell on an aircraft. By 1989, Sony had already applied for an exemption on the DOT rules, but in truth it wanted more than an exemption. It wanted a clean break from any reference to the old lithium metal primary battery. "There was significant motivation to refer to these chemistries as something other than lithium," noted Brian Barnett of Battery Perspectives LLC, who was familiar with Sony's effort. "They wanted to say there was no metallic lithium in their batteries. It was only lithium ions."

Many companies would later say they had coined the term "lithium-ion." Most likely, though, the term originated during a research and development meeting between Sony and one of its suppliers, the Kureha Corporation. That meeting then led to the first known public use of the name in a 1990 Sony technical paper titled

"Lithium Ion Rechargeable Battery."[64] The Sony paper laid the groundwork for the entire industry. It provided a name that would permanently stick. More, it served notice to the entire industry that metallic lithium was passé. From that point forward, the industry stopped working on metallic lithium primary batteries.

In February 1990, word began to trickle from Sony that it had developed a new battery chemistry. Few in the technical community or in the press reacted to it, however. It was, it seemed, still a story for the cognoscenti, the insiders. In the US, an ambitious trade publication called *American Metal Market* ran one of the first stories on it,[65] stating that the "new 'lithium-ion' rechargeable batteries" had an energy output four times greater than that of nickel–cadmium. The story added that Sony planned to manufacture a hundred thousand batteries per month and would spend the first year evaluating them.

A month later, with the story still getting little traction in North America, two Sony executives (Toru Nagaura and Keizaburo Tozawa) made a twenty-minute presentation at the Third International Rechargeable Battery Seminar in Deerfield Beach, Florida. They told a small audience of about a hundred attendees that the battery was rechargeable, operated at 4.1 volts, and had an energy density of 80 watt-hours per kilogram—more than twice that of nickel–cadmium. But the audience did not react in any noticeable way. "There was no feeling of anyone being awestruck," Arden Johnson, a battery researcher who attended the meeting for Battery Engineering Inc., said many years later. "No one felt like they were in the presence of something remarkable. It was just one more possible rechargeable technology."

To be sure, part of that indifference was caused by the unexpected nature of the news. Whereas many in Asia were already aware of the new rechargeable battery, there'd been virtually no buzz about it in the US. "When it was announced, it was a total surprise to almost everyone in North America," Barnett said. "No one saw it coming."

Within a year, however, that changed. On February 4, 1991, Sony released a press statement declaring that the battery was being rolled out to the market. All at once, North America became aware. One afternoon in February 1991 while changing planes in the Minneapolis–St. Paul airport, Barnett checked his voice mail from a pay phone and discovered multiple messages from industry contacts asking about Sony's new lithium battery. Now, the word was out. Within a few weeks, the buzz around the new battery grew much bigger. Toru Nagaura, one of the Sony research managers who had introduced the lithium-ion battery to a collective shrug at the Deerfield Beach conference a year earlier, was now a celebrity in the battery industry. "Nagaura came to the subsequent meeting in March 1991, and he was mobbed," Barnett said later. "Suddenly, everybody wanted to talk to him." For months after that, Nagaura would show up at conferences with a Sony camcorder powered by lithium-ion batteries. Every time he did, he drew a crowd. He traveled the world, talking about the lithium-ion battery and winning over the skeptics.

But the real action around lithium-ion was still in Japan. By 1991, Japanese manufacturers were already reaping the benefits. Because electronics manufacturers there had developed tight working relationships with battery makers, adoption of lithium-ion took off. Laptop makers realized that with lithium-ion, they could double the time between charges—from three to six hours. Cell phone makers saw the obvious size benefits. Thus, big manufacturers like Matsushita and Toshiba announced plans to use it in their products and quietly began laying plans to build their own such batteries.

Now it was official: The lithium-ion battery had arrived.

After Sony's announcements were made public, the importance and potential of the newly named lithium-ion battery began to dawn on the board members at Asahi Chemical.

The company's gradual recognition did not begin in house, however. It started, rather, when an intermediary contacted Isao Kuribayashi. The intermediary, Mitsui & Company, was one of Japan's largest *sogo shoshas*, or general trading companies. Mitsui's representative told Kuribayashi that Toshiba Corporation wanted to talk with him.[66] Toshiba, a technology company with a long history and a sprawling list of business interests, was one of the world's biggest manufacturers of personal computers and consumer electronics.

The meaning of the request was not lost on Kuribayashi. Toshiba had released the world's first laptop PC, the T1100, in 1985. The company was a leader in the portable PC market. And it, along with other laptop PC manufacturers, dearly wanted access to the new lithium-ion technology.

When Kuribayashi arrived by train for his meeting with Toshiba, he wasn't disappointed. Toshiba executives told him they already had joint ventures in place for other parts of their laptop computer—one for the "brain" (the microprocessor) and one for the "eye" (the display). Now, they sought another for the machine's "heart"—that is, the battery.[67]

For Kuribayashi, it was a critical moment. At this point, Sony was already ratcheting up production of its lithium-ion batteries, and Asahi was falling farther behind. It had already balked at a partnership with Varta AG. In many ways, the Toshiba contact was a stroke of exceptional good fortune, for him and the company. "I felt this opportunity might be the last chance for the team members to save the project team in Asahi Chemical and allow them to continue with this job," he wrote later.[68]

This time, the Asahi board agreed. Toshiba was a huge company with amazing resources. It had 168,000 employees, about seven times that of Asahi. In 1991, its sales were $37.8 billion, about forty-five times that of Asahi. It was essentially a much bigger brother to a company that clearly feared it was incapable of making the journey alone. Toshiba would be there to share the risk. *And* it was Japanese. Within three weeks, the two companies agreed to a joint feasibility study. It was too late to catch Sony, of course. By September 30, 1991, when Asahi and Toshiba announced their feasibility study,[69] Sony was already producing a hundred thousand batteries a year. Twelve months later, with the feasibility study finished, Asahi and Toshiba would officially announce an equal split joint venture called A&T Battery (ATB).[70]

ATB was an ambitious start-up. Plans were for it to produce five hundred thousand batteries a month by late 1993 and to climb to $240 million in annual sales by 1997. But again, Sony would still be far ahead. By late 1992, Sony was working its way to a million units a year, with plans to raise that to as much as five million by 1996.[71]

Gradually, ATB began to scale up its production. It started by building so-called 18650 cells (cylindrical cells eighteen millimeters in diameter and sixty-five millimeters high—about the size of an adult's finger). It delivered twenty thousand sets of battery packs to Sony, which had been requested four years earlier. And it started work on prismatic cells (thin rectangular cells) for mobile phones. The Japanese audio company Kenwood Corporation requested delivery of two thousand packs per month, with plans to quickly increase to twenty thousand per month. Asahi's rechargeable lithium battery was finally happening.

Thus, Asahi Chemical board members were satisfied. True, they'd been beaten to the market by a technology that they believed they had invented. But they said they didn't mind being second. They'd staked out an early position. And, as they viewed it, they were following Sony, letting them make the early errors.

So while it was clear they'd fumbled the opportunity to be first to market, it was also true that they'd made no major errors. They'd minimized their risk. They'd saved face. "Just like the second runner 'drafting' in a track and field competition, our wind guard would be Sony," Kuribayashi wrote.[72]

It was a monumental effort, but it would never quite be recognized that way. Hundreds of scientists and engineers at Asahi Chemical, Sony, and supplier companies had created a product where there'd been none previously. They'd taken a cathode and turned it into a full battery. They'd created the anode, engineered the electrolyte, developed the separator and binders. They'd made a commercially viable concept.

In the US and UK, however, some scientists and engineers lamented. They felt the concept was theirs, and the business had been theirs for the taking, too. To them, it was a case of missed opportunity. They'd mastered the science first and had let it slip away. In some ways, it was reminiscent of the microchip, they said. The transistor had been invented at Bell Labs in the US in 1947, yet the market had come to be dominated by Asian manufacturers who'd been more ambitious. And here it was happening again. In essence, many of the scientists in the US and UK believed that the rechargeable lithium battery was all but completed when it left Oxford University and that Japanese manufacturers had merely assembled the pieces.[73]

That, of course, wasn't true. But their belief was rooted in the traditional view of research and development, or R&D. Specifically, it came from the so-called linear model of R&D. In the linear model, there was a big "R" and a small "d." Research, especially *fundamental* research, was believed to be the lone source of breakthroughs. It was knowledge for knowledge's sake, and it was the origin of Nobel Prizes. In contrast, development was merely *applied* research and engineering. It tended to be more commercial, more product oriented. It was the province of mere mortals. In this case, it was believed that the scientists had done the heavy lifting, and the Japanese engineers had come along and walked away with it.

Such beliefs had been common for decades, going back to a famed US national science advisor named Vannevar Bush.[74] Bush had served under President Harry Truman after World War II and had espoused the philosophy of linear R&D. He had said that the Manhattan Project, which had produced the atomic bomb that ended the war, was a perfect example of it. There, he said, research had led engineering. And he believed that American industry would be well served to emulate that model. Bush's belief had been so influential that many big American corporations had set up research facilities that were physically isolated from corporate headquarters and product development centers. The high-level assumption was that scientists needed to be left to their own devices and should not be subjected to business-related meddling. General Electric, General Motors, DuPont, Xerox, IBM, Eastman Kodak, and Texas Instruments all had their own grand research laboratories. Even Ford Motor Company, not known as a research mecca, had opened its own 720-acre Research and Engineering Center in 1951. Increasingly in the 1940s and '50s, the belief had been that unrestrained fundamental research was a sort of secret sauce for big companies seeking technological preeminence.

And it often worked. The granddaddy of such facilities was General Electric's lab, the nation's oldest industrial research center. GE's labs had developed centralized electricity generation, motion pictures, practical telephone transducers, incandescent electric lamps, and ductile tungsten, among many other innovations. Similarly, General Motors Research Laboratories had contributed to the first computer operating system and the first mechanical heart. And then there was Bell Telephone Laboratories in Murray Hill, New Jersey. Bell Labs' achievements would eventually include nine Nobel Prizes. Its inventors were credited with radio astronomy, early versions of the laser, the first practical photovoltaic cell, and the biggest of all, the transistor in 1947. Similarly, Texas Instruments, DuPont, and IBM had all made major breakthroughs at their labs.

But the truth was that not *all* innovation obeyed the linear model. As explained by author Henry Petroski in *The Essential Engineer*, the best example was the US space program, which had not been the product of fundamental research, but rather had been inspired by a national desire to catch the Soviets after the Sputnik launch.[75] It was, in the truest sense, an engineering effort, yet it had yielded countless breakthrough technologies. *Scientific* breakthroughs. There were other examples in the 1960s of rocketry and aerospace. Thus, Bush himself came to rethink the linear model by the mid-1960s.[76] "While everyone knows that engineering is concerned with the conversion of science into technology, everyone does not know that engineering does just the opposite and translates technology into new science and mathematics," Bush said later.[77] He eventually reached the conclusion that science and engineering were not parent and child, but rather, equal partners.

Such was the case with the rechargeable lithium battery. Fundamental research, applied research, and engineering all contributed mightily. The Japanese development effort, in particular, had yielded countless materials science breakthroughs. It had shown that there were no upper and lower plateaus of innovation. The cathodes, anodes, electrolytes, and the concept of the intercalation battery were all critically important. And the science behind those components had all been enhanced in Japan

Moreover, there hadn't been a linear progression from fundamental research to applied research to engineering. Ford Motor had given birth to the idea of fast ion transport in what could best be described as applied research. Then the idea had zigzagged back and forth between fundamental and applied research, from Ford to Stanford to Exxon to Oxford to France and elsewhere, before finally reaching Japan. Thus, it wasn't a case of pure R&D; it was R&D&R&D&R&D. There was nothing linear about it.

Had the rechargeable lithium battery been invented by a single individual and then been neatly delivered to engineers for refinement, it might have been a different story. But the lithium battery had not come to fruition in such a way. It had been invented in discrete pieces at different times, in different places. Thus, there was no scientific hierarchy. All of the pieces had been functionally critical.

The desire to view it more simply, however, would never die. Academic journals tended to credit a few scientists as the inventors. News accounts ascribed the invention to local favorites. And somehow, the people who had breathed life into the commercial product in Japan were considered a less important part of the story. They had merely *commercialized* it.

To some degree, Japanese manufacturers contributed to that false impression. They'd been so quiet, so covert, so reticent to share their findings with the battery community that the rest of the scientific world had been unaware of their effort until the lithium-ion battery emerged as a product. By the time the product was rolled out to the world, it looked to outsiders as if it must have been easier than it really was.

But the truth was, there was no big "R" and small "d." There was no parent and child. Without the efforts of Asahi Chemical and Sony, the lithium-ion battery might not have reached the product stage for at least another decade.

But in 1991, it had arrived, in large put due to an enormous research effort by Japanese manufacturers.

Although Sony had been first to market with lithium-ion, and although it was virtually alone in the beginning, Yoshio Nishi did not feel comfortable. By the time Sony had started selling lithium-ion batteries, Nishi had been with Sony for a quarter century, and he understood that in the ferocious Japanese market, no one stayed on top for very long without competition.

He was, by all accounts, a dedicated corporate soldier. He had grown up wanting to be a scientist and could remember as far back as junior high school doing experiments on the influence of water temperature on the oxygen uptake of goldfish.[78] After graduating from Keio University in 1966, he had joined Sony in hopes of doing materials science work on semiconductor materials. But when that hadn't happened, and Sony had assigned him instead to do research work on zinc–air batteries, he had accepted the role in stoic fashion, without complaint. Later, when he'd been transferred to electroacoustics and had worked on materials for loudspeakers and microphones, he had again performed well, despite not being completely satisfied. Loudspeaker research didn't have the technical cachet of semiconductor work, but he had persevered. In a sense, it had been good for him. In the course of doing that work for two decades, he had learned about the ruthless and competitive nature of the Japanese market, and about the dangers of complacency. Thus, he knew that now was no time for Sony to rest. Besides, he understood there were others out there—A&T Battery, Sanyo Electric, Matsushita Electric, NEC Corporation, and Hitachi Maxell—already targeting the lithium-ion market.

Nishi believed that Sony's main vulnerability was its anode. He wasn't satisfied with petroleum coke, or "soft carbon," as it was known. Soft carbon offered good energy density, about 80 watt-hours per kilogram, which was better than nickel–cadmium and nickel–metal hydride. But he believed Sony could do better, significantly better. And he had begun to work with Kureha Corporation on an alternative. The alternative was hard carbon. Hard carbon differed from soft carbon in that it was not "graphitizable"—that is, no matter how much heat was applied to it, it would not change into graphite. Soft carbon, in contrast, was graphitizable. But the important aspect of hard carbon was that the spacing between its disordered molecular layers was broader than that of soft carbon, and more lithium ions could be squeezed within those layers. That, in turn, translated to greater energy. It could be charged to 4.2 volts, and its energy density was about 120 watt-hours per kilogram. In essence, its capacity was about 50 percent greater than that of soft carbon.

The importance of this was not lost on Nishi. Battery scientists, going all the way back to the days of Edison, had been clawing their way up the energy density scale in small increments. A boost of ten watt-hours per kilogram was considered a major gain. And now here, in a matter of just a few months, he had found a way to increase the world's best rechargeable battery by a whopping forty watt-hours per kilogram, a 50 percent bump.

So it was that by 1992 it was inevitable that Sony would introduce a lithium-ion battery with a hard carbon anode. Sony's battery developers weren't finished, however. Now, they began to look for a new format, a new shape, for the battery. To date, most of Sony's lithium-ion batteries had been the finger-sized 18650 style. But now they wanted to move beyond the cylindrical shape. Mobile phone sales were growing rapidly and phone manufacturers wanted to transition to a prismatic battery—that is, a flat rectangular battery. Prismatic was the desired format for all cell phone makers. Flat batteries wasted less internal space than cylindrical batteries. Here, however, Nishi began to feel a pushback from Sony's business side. The business division didn't like the idea.[79] They had previously manufactured flat batteries, so-called chewing gum batteries for the Sony Walkman, and they hadn't sold well. Moreover, prismatic batteries would require an aluminum "can" (container), as well as alterations to the manufacturing line.[80] Why, they asked, couldn't the engineers be satisfied with the company's current level of success? The cylindrical, finger-sized lithium-ion batteries were, after all, selling quite well.

Nishi listened to all of the excuses and decided that complacency was already creeping in. In evaluating the situation, he later wrote that "success is the cause of failure."[81] It was either that, or the executives simply didn't understand how vast the market for lithium-ion could be, he thought. Either way, Nishi wasn't giving up. He could imagine a market in which lithium-ion could be used in many new applications, beyond camcorders and notebook computers. And he wanted to make sure Sony was ready for it. There was, he thought, more to be done.

He wasn't satisfied with the lithium-ion battery just yet.

Rachid Yazami didn't hear about Sony's battery until late in the spring of 1990. Attending the Fifth International Meeting on Lithium Batteries in Beijing, Yazami kept overhearing the buzz—Sony would release its lithium battery as a commercial product in 1991. This was already three months after Sony had delivered its first technical paper on the battery in Deerfield Beach, Florida, but somehow the word hadn't immediately gotten to Yazami, who was now temporarily living in Japan.

By this time, more than a decade had passed since Yazami had done his studies on the intercalation of lithium into graphite in France. He had finished his PhD and had earned a lifetime appointment at the French National Center for Scientific Research. Despite the disappointment of having been told that his graphite anode had no future, he'd stuck with it over the passing years. He was attending the Beijing meeting as a presenter, having been slated to give a paper on the use of graphite in lithium batteries. At this point, however, he had reached the inescapable conclusion that his graphite electrode could not be used in the way that most battery developers wanted. "In a liquid electrolyte, you can't use graphite," he told scientists at the conference. "It won't work." The problem, he said, was that most developers wanted to use liquid electrolytes, which would cause the graphite to swell.

Graphite, however, was a form of carbon, so when Yazami heard about Sony's battery and its carbon anode, he wanted to know more. But Sony had no representatives at the Beijing conference. All of his information was secondhand. Yazami therefore called a former student of his who was now working at Sony. After the former student nervously explained he wasn't allowed to divulge information, he passed the call to his boss. The boss was Yoshio Nishi.

Yazami was surprised to find not only that Nishi had heard of him but that he wanted to talk. Moreover, Nishi wanted to set up a meeting. "I can't tell you anything over the phone," Nishi said. "But why don't you come out and visit us?" Nishi had good reasons for wanting to meet with Yazami. He was already looking beyond not only soft carbon anodes but hard carbon as well. And Nishi suspected that graphite might be the next big frontier. Moreover, he had heard that others in Japan were working on graphite. Sanyo Electric Company, in particular, had begun filing Japanese patents in 1981 that alluded to the use of graphite anodes.[82] And a paper published by well-known battery developer Jeff Dahn in 1990 pointed researchers to a new liquid electrolyte that might make graphite a real possibility.[83] If that was true, it would mean that the industry might be on the verge of another big improvement in lithium-ion battery technology.

In July of 1990, Yazami traveled to the Sony Research Center in Yokohama. When he arrived, he was shocked. A scrolling message on an electronic sign outside the lab said, "Sony is very happy to welcome Professor Yazami." Inside, Sony executives rolled out the red carpet. They asked him to make a brief presentation to an audience of engineers, then invited him to lunch at one of the best restaurants in Yokohama. After lunch, they brought him back to a massive, oval-shaped conference room and walked him to a long table. If it hadn't yet dawned on Yazami that he was an important guest, it now became very clear. One by one, engineers stepped up, bowed, and presented their business cards with two hands. When they finished, they directed Yazami to sit on one side of the conference table, while thirty engineers faced him from the other side. Sony attendees were arranged in order of importance, starting from the middle and moving out. Yoshio Nishi, the director, sat in the middle. The outermost individuals wore red armbands, signifying that they were junior staff members, and were not encouraged to offer opinions. "I said, 'Why don't you come and sit with me?' Yazami recalled many years later. "'I don't want to sit alone.' But they said, 'No, no, this is how it works.'"

Nishi thanked Yazami for his presentation and explained that Yazami was the first scholar, Japanese or otherwise, to hear the specifics of Sony's upcoming battery introduction. Nishi offered all the details—the lithium cobalt oxide cathode, the carbon anode, the electrolyte, separator, binders, everything. Moreover, he did not ask Yazami to sign a nondisclosure agreement. Yazami was apparently too important to be treated with such formalities.

Finally, Yazami asked if Sony was planning to use "my graphite anode" in its future batteries. "Nishi said, 'We aren't yet, but we're thinking about it,'" Yazami recalled. Nishi then came to the point of the meeting. Sony, he said, wanted to sponsor Yazami's research on graphite anodes. Nishi even offered to send a Sony scientist, a postdoc, to help with the research for one year. A collaborative agreement was finalized, a small step toward enabling Sony to lay the foundation for a graphite anode.

Yazami would spend the next twelve months working in Grenoble, France, on his graphite anode, aided by his Sony postdoc. Occasionally he traveled back and forth to Sony's Yokohama Research Center. During that year, Yazami and Sony would learn what others were already finding about graphite: that the graphite anode *could* be used with a liquid electrolyte, if the right electrolyte was selected.

Up to that point in battery history, scientists had largely focused on anodes and cathodes. Anodes and cathodes were the meat and potatoes of the battery. Now, however, they were realizing that the electrolyte mattered more than they had ever known. With the right electrolyte, they could employ a better anode. And the right electrolyte was now within their grasp. In a 1991 Japanese patent, Sanyo described a lithium-ion battery with a graphite anode and a workable liquid electrolyte. The electrolyte consisted of lithium salts dissolved in a solvent that used ethylene carbonate (EC). In ethylene carbonate, they had learned, graphite did not swell.

Over time, Sony would successfully develop a graphite anode. Thus by 1992, with its hard carbon anode just reaching the market, it was already looking forward to the launch of a lithium-ion battery with a graphite anode. Graphite would turn out to be another remarkable step forward. It was more readily available and less costly than petroleum coke or hard carbon, and it offered another big bump up in energy density. The battery's energy density would now top out at 155 watt-hours per kilogram—almost twice that of Sony's first-generation battery.

But Sony executives, who had moved with such decisiveness and urgency only a few years earlier, were now balking. Nishi's requests were increasingly met by resistance and delays. "'Why do we need to change if we are successful in [hard carbon]?'" they asked Nishi.[84] It was as if the market was now moving too fast, even for the very company that had led the way to the commercial lithium-ion battery. The company, Nishi later wrote, was "drunk with the success of cylindrical [lithium-ion] batteries."[85]

Thus, by the time Sony would be ready to bring its graphite anode to market, it would be beaten at its own game. In 1993, Sanyo would roll out its own lithium-ion battery—one with a graphite anode. While Sony was moving from its first to its second generation, Sanyo had quietly passed it. By early 1993, Sanyo was producing five hundred thousand batteries a month, with plans to go to a million. Moreover, its batteries were appearing in many applications. Whereas Sony had focused on batteries for its CCD-TR1 camcorder, Sanyo was selling them for video cameras, laptop computers, and wireless phones.

The emergence of Sanyo was only the beginning, however. As if out of nowhere, the lithium-ion battery market in Japan began expanding at an extraordinary rate. It wasn't just Sony and A&T Battery anymore. Nor was Sanyo the only newcomer. Matsushita Electric, NEC Corporation, GS Yuasa Corporation, and Hitachi Maxell were now all planning lithium-ion rollouts as well. The pace of innovation had become frantic and the competition was suddenly ferocious. When Sony rolled out its third-generation battery in 1995, the lithium-ion market was just four years old. The energy density of the lithium-ion battery had doubled in those four years. The lithium-ion battery was now far ahead of other chemistries—nickel–metal hydride and nickel–cadmium—if not in sales, certainly in terms of capability. At long last, the world was discovering lithium-ion.

By this time, everyone in the lithium-ion market knew that the graphite anode was the future. The technology had finally blossomed, fifteen years after Rachid Yazami said he had inserted lithium in graphite. And the technology would remain dominant for decades, one of the few elements of the lithium-ion battery that would not change. By 2019, ten billion lithium-ion cells per year would use graphite. Credit for the invention of the graphite anode, however, would always remain unclear. Sanyo had written it into patents in 1981, and Samar Basu of AT&T Bell Labs had done the same in 1983.[86] Yazami, whose patent effort had been discouraged as "worthless" in 1980, would join with many others in lithium-ion history who would never benefit financially from their discoveries. "If they gave me one-thousandth of a penny for each battery that was made, I'd be doing quite well," Yazami would say with a wry smile many years later. "But we are university people. We are scholars, so we don't care about money."

So it was, only four years after Sony's introduction of the lithium-ion battery in 1991, a big new market had emerged. Notebook computers with color displays took off, seemingly overnight, as manufacturers like Toshiba and Dell employed lithium-ion. Smaller, lighter camcorders rolled out, weighing as little as 1.3 pounds, thanks to the lithium-ion battery. Motorola, meanwhile, introduced a cell phone called the MicroTAC Elite, weighing just 3.9 ounces. The MicroTAC was able to deliver sixty minutes of talk time, again thanks to lithium-ion. It was, in essence, a eureka moment for the worldwide battery community.

Still, a big challenge remained. The electronics industry, with its little phones and notebook computers, was small in terms of market potential when compared to the auto industry. Whereas a phone might use a battery weighing just an ounce or two, one electric car would likely need more than a thousand *pounds* of batteries. The market potential was enormous. The US auto market alone sold more than ten million cars a year, and there were hundreds of millions of cars on roads worldwide.

None of this was lost on the engineers at Sony. Late in 1995, Sony announced its engineers were working on lithium-ion battery modules for electric vehicles.[87] By April 1996, it had teamed with Nissan Motor Company Ltd. to develop a battery for a four-seat electric demonstration vehicle called the FEV II.[88] It would be the first vehicle to use a lithium-ion battery pack and would offer a 124-mile range, which was about 80 miles more than it could have offered with a state-of-the-art lead–acid battery. To be sure, there were challenges ahead. The estimated cost of Sony's battery pack was more than $100,000, and even that was said to be an optimistic figure.

For the moment, however, that didn't matter. The day of the lithium-ion-powered vehicle was approaching.

All that remained was for the rest of the world to recognize it.

Part II

The Heart of the Electric Car

"There is a tide in the affairs of men, which, taken at the flood, leads on to fortune. Omitted, all the voyage of their life is bound in shallows and in miseries. On such a full sea we are now afloat, and we must take the current when it serves, or lose our ventures."

WILLIAM SHAKESPEARE, FROM *JULIUS CAESAR*

6

The Electric Car Quest

The man responsible for the 1990s revival of the electric car was a most unlikely candidate for the role. Roger B. Smith was not an environmentalist, a political ideologue, a scientist, or an engineer. He had no plan to change the nature of transportation.

Smith was, however, the chairman of General Motors. And, as chairman, he had been the recipient of glowing reports about an internal program known as Project Santana, an all-electric car purported to have a 120-mile driving range. Fifteen months earlier, Smith had reluctantly committed $3 million to Santana, then had carefully followed its development. His engineers, in part trying to justify the funding, had delivered a succession of optimistic reports, and in response Smith had unexpectedly decided to unveil the Santana EV at the Los Angeles Auto Show in January 1990.

The decision sent shock waves through the highest levels of General Motors. One by one, GM's highest-ranking engineers had tried to carefully dissuade the chairman. Author Michael Shnayerson, who later chronicled the birth of GM's new electric car in the book *The Car That Could*, wrote that Robert Stempel, Lloyd Reuss, Don Runkle, and Don Atwood were all among the car's most enthusiastic supporters, yet each visited Smith and cautioned him against going public with it.[1] They emphasized the need for secrecy. There were many reasons for not going public, they said, the most important of which was they didn't want to arouse the interest of the California Air Resources Board (CARB). GM was already tussling with CARB over other matters, and they didn't want to give CARB's environmentalists any more food for thought.

Smith, however, was not about to listen to the excuses of engineers. Not an engineer himself, he intuitively felt that engineers were too often focused on small matters, unable to see the bigger picture. "Most engineers would still be working away on the 1971 Chevrolet if someone hadn't grabbed it away from them," he had once said.[2] In truth, no one would ever be sure of his full reasoning on the matter, but it was assumed he wanted to give GM a badly needed public relations boost. In the previous eight years under Smith's chairmanship, GM's share of the US auto market had dropped precipitously, from 46 to 35 percent. Worse, consumer groups were citing the company for poor vehicle reliability. And then there had been the movie *Roger & Me*, a satiric documentary depicting the decline of Flint, Michigan. *Roger & Me* placed much of the blame for the situation on Smith in particular. Despite a penchant for oversimplification, the film succeeded mightily in making GM and Smith appear greedy and uncaring about the plight of its own employees.

So it was that on January 3, 1990, Smith personally announced at a news conference in Los Angeles that GM had built an amazing new prototype EV (electric vehicle). By this time, the name Santana had been dropped and hastily replaced with GM Impact. And the diminutive Smith, in his characteristic high-pitched tones, delivered an effusive report on the new electric car. "We've taken a big step, a very big step here," he told reporters.[3] He showed a videotape of the prototype Impact outracing a Mazda Miata and a Nissan 300 ZX from a standing start to sixty miles per hour. He then said that he would be most comfortable if GM produced a hundred thousand Impacts a year, rather than a mere twenty thousand. He concluded by addressing the oft heard criticism of EVs of the day: "This is no golf cart," he told reporters.

The nationwide reaction to the introduction was almost instantaneous. The *New York Times* ran a story, as did the *Wall Street Journal*. National news broadcasts covered it, placing Roger Smith front and center. Environmentalists praised GM. The news even had a comic side to it. Many in the media pounced on the car's name, the Impact, citing its unintentional double entendre, with the most inspired rendition of the day coming from the *Tonight Show*'s Johnny Carson. "What next?" Carson asked. "The Ford Whiplash?"

Suddenly, the nation knew of the GM Impact. And Roger Smith loved it. In April he convened another press conference at the National Press Club in Washington, DC, to tell the media that GM would build and sell a production version of the Impact. He declared that the company had set "an aggressive schedule" to solve all technical issues and said that the car "will play an important role in meeting our country's transportation needs and environmental goals."[4]

Now the die was cast. Not only did GM have a prototype electric car; it now planned to build and sell it. This was everything the GM engineers had feared. For years they had battled with federal and state governments over tailpipe emissions and fuel efficiencies. And now the cost of changes wrought by those regulations would be small compared to the costs associated with an electric car mandate. In their minds, the difference between an experimental electric concept car and a real production car was enormous and obvious, but they almost universally doubted that the people at CARB, whom they regarded as eggheads, would recognize those differences. In truth, CARB was a small government agency with a board that included a medical expert, an agriculturalist, and a few county supervisors, but not a single automotive engineer.[5] Its internal knowledge on the state of electric cars was not likely to be substantial, they thought.

In a few months, the fears of GM engineers were realized. A thick CARB document released on September 28, 1990, included, almost as an afterthought, one extraordinary page.[6] On that page, the agency ruled that in 1998, each of the world's seven biggest automakers would be called upon to make 2 percent of their vehicles emission-free. Then it got worse: In 2001, the number would climb to 5 percent; and in 2003, a whopping 10 percent.

Engineers across the auto industry were stunned. Zero-emission almost certainly meant electric car. And all automakers, including GM, were woefully far from being able to design, build, and manufacture a commercially competitive electric car at any time in the future, let alone in six years. The worst part of the CARB declaration was that it called on automakers not only to produce the electric cars but to *sell* them as well. This was a matter they couldn't control. Yes, they could build electric cars, but they couldn't force anyone to buy them, especially if there was no breakthrough technical solution between now and then. Automakers feared they might nearly have to *give* the cars away in order to reach the 2 percent mandate.

But GM, in particular, was in no position to argue the mandate. Its chairman, after all, had said the company was ready to build. He had said GM's new car would play an important role in meeting the country's environmental goals. He had declared he would be comfortable if the company sold a hundred thousand EVs a year. He had shown a videotape of GM's electric car roaring past the sportiest cars of the era. And he had delivered the conclusion: "This is no golf cart."

Moreover, the environmental lobby had praised GM, and Smith had gloried in the praise. "What this shows is that a major corporation recognizes that California is serious in demanding clean cars and clean fuel," noted a spokesman for the South Coast Air Quality Management District of California.[7] And GM had accepted the praise that was heaped upon it.

Thanks to Roger Smith, the auto industry would now have to deliver electric cars. A lot of them.

By the time CARB unveiled its radical document on September 28, 1990, Ford Motor Company had already been hard at work on an EV for nearly a year. Its new vehicle, an electrified Ecostar delivery van, was the culmination of a research effort the company had launched nearly a quarter century earlier.

The sodium–sulfur battery, the product of that research effort, had been languishing in Ford labs since 1963. Amazingly, it had survived all those years, and was still recognized for its ability to deliver higher levels of energy than any known battery chemistry of the day. At this point, the work of Sony and Asahi Chemical on lithium-ion batteries was still virtually unknown. Thus, sodium–sulfur appeared to be the most promising of high-energy rechargeable battery chemistries, at least as far as anyone knew.

By fall of 1989, however, the researchers who had discovered and patented sodium–sulfur had mostly retired or moved on. Joe Kummer, the six-foot, eight-inch Ford materials engineer widely regarded as the inventor of sodium–sulfur, had retired in 1984. Neill Weber, the coinventor who had posed with Kummer for a black-and-white *Life* magazine layout in 1966, had also left. Most of the reporters who had written about sodium–sulfur and cited it as the future of transportation had moved on as well.

But sodium–sulfur had not been forgotten at Ford. Everyone in Ford's research labs remembered it. Most recalled it with some fondness; it had vaulted Ford researchers to national prominence at one point. And now, at long last, its day was finally coming. It was moving from the realm of research to the world of engineering. Now, the world would find out if sodium–sulfur really *was* the future of automotive transportation.

In 1989, Ford began to assemble a team to breathe life into its new electric car. The team included vehicle engineers, powertrain engineers, and controls engineers, one of which was a twelve-year Ford veteran named Joe Burba. Burba had been recruited straight off the campus of Oklahoma State University by Ford in 1977. By education, he was an electrical engineer. That made him different from most automotive engineers of the day, who were largely educated in mechanical engineering. That also made him more accepting, and even enthusiastic, about the development of an electric car. Burba's specialty was in rotating machinery, specifically in the computerized control of electric motors. More specifically, his area of expertise was called embedded systems—the incorporation of microprocessors and software into machinery. This was a technical discipline so new that it hadn't even existed back when Joe Kummer had invented sodium–sulfur.

After joining Ford in Dearborn, Michigan, Burba had initially settled into a manufacturing role. Then, he filled out a "developmental interest survey" in 1979, and Ford unexpectedly transferred him to its EV research staff. "They showed me to my new desk, which was a surprise to me, since I hadn't even accepted the position yet," Burba would recall many years later.

In EVs, Burba found a home. Whereas many automotive engineers of the day steered clear of EVs because they saw them as a dead end, Burba was happy to be there. He knew that Ford's EV program had existed since the mid-1960s, and he correctly guessed that such programs would gain momentum over time. He started by working on a controller for an EV's DC shunt motor. Here, he could employ his knowledge of embedded systems. The controller would enable the motor to run a programmed acceleration schedule. For Burba, with his technical background, it was a relatively simple task, and it took him about two weeks. He later learned, however, that Ford had been working on the task unsuccessfully for about six months before he'd arrived. Thus, Burba was quickly designated an in-house expert. He was an engineer who intuitively understood the operation of the electric motors that powered EVs.

But it wasn't until 1989 that Burba took on a bigger role in Ford's EV effort. That was when Ford decided to electrify the Ecostar, a small European delivery van that seemed like an ideal test bed for an EV. The Ecostar had a flat open surface at the rear of its interior, which made it a logical candidate for a big battery pack. Burba was named lead systems engineer for the design of the vehicle's electrical architecture. Later, he was promoted to supervisor of powertrain systems.

From the beginning, Burba and the Ecostar team had wanted to employ a sodium–sulfur battery. Sodium–sulfur was the most promising chemistry for a long-range electric car. Moreover, it had been invented at Ford. The team quickly concluded, however, that the fundamental battery work done on the lab benches at Ford's Scientific Research Laboratory in the 1960s was not suited for a production battery. They therefore contracted the battery's development work out to Asea Brown Boveri, a Zurich-based conglomerate that specialized in electrification and industrial automation. While ABB developed a productionized version of the battery, Ford engineers continued to work on the Ecostar van using a lead–acid battery pack to temporarily serve in place of sodium–sulfur.

The resulting vehicle was one that, in many ways, was far ahead of its time. Led by Burba, the Ford team developed one of the most advanced vehicle control systems of the day, one using seven microprocessors to run everything from the battery to the instrument panel to the diagnostics module. Thirty years later, of course, vehicles would routinely employ dozens of microprocessors, but in 1991, seven was extraordinary. "Ecostar has five times the computer power of the most advanced Ford on the road today," noted Harold A. Poling, Ford's chairman and chief executive officer.[8] In essence, Ecostar used electronics and software to replace many of the mechanical systems used on conventional vehicles. Therefore, when ABB started delivering battery packs in November 1992, the Ecostar team already had a controller waiting. All that remained was to reprogram it for the new sodium–sulfur battery.

For Ford engineers, the sodium–sulfur battery pack was a sight to behold. It consisted of a large rectangular stainless steel case, slightly less than two feet high, mounted under the Ecostar's load floor. The case actually had two walls—one inside the other—making it like a giant thermos bottle. Inside were 280 stainless steel, cigar-shaped tubes. These were the battery's cells. Inside the cells were two molten liquids—sodium and sulfur—separated by a solid ceramic electrolyte known as beta alumina. As the battery charged and discharged, sodium ions passed back and forth through the miniscule voids in the beta alumina, thus enabling the battery to deliver electrical current to an external circuit. The current from the external circuit powered the motor that turned the car's wheels.

The tricky part of the sodium–sulfur battery pack was that it needed to be both heated and cooled. Heat was critical. The sodium and sulfur electrodes had to be kept in a molten state in order to deliver power. They required temperatures in excess of 550 degrees Fahrenheit. Thus, a sensor monitored the pack's temperatures and, if necessary, engaged an electric resistance heater whenever the pack grew too cold. At the same time, a cooling system was needed to prevent the pack from getting too hot under certain driving conditions. The solution was a cooling plate on the underside of the stainless steel "thermos." A pump circulated a machine oil called Marlotherm through channels in the plate, enabling it to draw heat away from the cells. The heating and cooling had to be carefully balanced, however—too much heat was a fire risk and sudden cooling could cause the battery's ceramic electrolyte to fracture. Therefore, the temperature control system constantly monitored the battery, even when the car was turned off. "It was quite a thermal management challenge," Burba said many years later. "You had to keep it cool, you had to keep it hot, and you had to maintain a constant temperature to the extent possible. You couldn't allow the temperature to change too fast."

Ford engineers considered the engineering challenges to be a small price to pay for the battery's power. Their pack offered thirty-seven kilowatt-hours of energy, more than they could have gotten with any battery of the day, and it produced a driving range of anywhere from 100 to 155 miles, depending on how they drove it. There was nothing remotely close to it at the time. Lead–acid packs were producing only about 40 miles.

By April 1993, Ford's team began running the Ecostar on a test track in Dearborn. The goal was to operate it continuously for 150,000 miles. For weeks in the spring of '93, engineers drove it day and night, finally tallying 150,000 miles and chronicling only a handful of failures. Next, they took the vehicle to Arizona to run it in hot weather conditions, operating the vehicle's air conditioner while they drove. Finally, they took it to the Upper Peninsula of Michigan and ran it in cold weather. Their conclusion was that weather affected its range, but little else. Throughout the tests, the sodium–sulfur battery appeared safe.

By this time, hundreds of people were working on the Ecostar program. Enthusiasm within Ford was rising. Initially, team members met once a week to go over problems and solutions, but as time moved on, the meetings came to be daily. There was a growing feeling that they might be on to something important, not only for Ford, but for the entire auto industry. In June, Ford began final assembly of the first 105 Ecostars, which the company intended to test in fleets with willing customers. As it turned out, however, the vehicles were more than just a test bed for the sodium–sulfur battery. They were viable products. In addition to the 770-pound battery pack, each vehicle contained a regenerative braking system, low rolling resistance tires, electrically driven air conditioner, AC induction motor, high-efficiency thermal windows, rack-and-pinion steering, fuel-fired heater, onboard charger, stereo cassette player, and an AM/FM radio. They even added a strip of solar cells across the top of the windshield to power an exhaust fan that cooled the interior when the car was parked in the sun. Ford engineers had intentionally included virtually every luxury car amenity of the day, and then some.

To provide real-world testing, Ford leased sixty-eight of the vehicles to fleet customers. United Parcel Service, Detroit Edison Company, the US Post Office, Southern California Edison, the Electric Power Research Institute, and the California Air Resources Board leased vehicles. Ford also produced two hybrid versions of the Ecostar on a US Department of Energy contract.

Ford executives, however, were careful not to overstate their growing enthusiasm for the program. Like the GM engineers who had feared misunderstandings on the part of CARB and the EPA, they knew they needed to be subdued in their public statements. Therefore, they were open about the Ecostar's shortcomings, such as its exorbitant cost. Lessees, they said, paid $100,000 for a thirty-month lease.[9] The battery alone, they added, was priced at $46,000 and might have to be replaced every two years. John Wallace, a high-level Ford executive who was one of the car's biggest backers, had gone out of his way to downplay the vehicle's significance to the press. "There are no breakthroughs in batteries," Wallace told the *Detroit Free Press*. "It's more like old-style Michigan football. You get three yards, over and over again. We're just going to have to slog it out. I don't know how long it will take."[10] Ford's EV segment manager, Dennis Wilkie, even went to the extent of adding, "Electric technology has *not* arrived."[11]

For the automotive media, however, the Ecostar turned out to be a great story. In light of the CARB's zero-emission vehicles mandate, there was a sense of urgency, and the urgency was not lost on the national press. Every move toward electrification by the big automakers was now covered in detail. Ford and GM were the two early leaders in this area, but Ford was especially interesting to reporters because of its use of sodium–sulfur. Automotive reporters who tested the Ecostar seized on this fact and dutifully reported that the Ford vehicles were getting an "honest" hundred-mile range, which was more than twice what they would have expected with other battery chemistries of the day. "It works exactly as advertised: a seventy-mile-per-hour (governed) freeway speed, a one hundred-plus-mile operating range, and a six to seven-hour recharge time (on a 240-volt circuit)," wrote *Car & Driver*.[12] Even if the Ecostar didn't offer the performance that appealed to readers of enthusiast magazines, it nevertheless had all the elements of a great story—timeliness and exotic technology, atop an emotionally pitched environmental battle. The coverage peaked in 1994, after the electric Ecostar won a New York to Philadelphia electric car race called the American Tour de Sol.

Ford's decision to downplay the Ecostar, however, ultimately turned out to be a wise one. On May 2, 1994, an Ecostar leased to the Electric Power Research Institute in Palo Alto caught fire while being recharged, and the news quickly spread to media around the country. A Ford statement blamed the fire on that particular battery's "different production procedure" and stated that "no other battery in today's fleet employs cells built with the same" process.[13] Ford added that there was no danger; other lessees had no reason for concern. Had that been true, it likely would have been the end of the story.

Unfortunately, it wasn't. In June, an Ecostar leased to the California Air Resources Board (CARB) caught fire while recharging. Now the story had an ironic twist: The organization mandating EV compliance had experienced an electric car fire. This time, Ford was forced to act. "Because of this second occurrence, Ford has decided to suspend use of the vehicles until it understands and can correct the underlying cause of the problem," Ford wrote in a statement.[14] With each passing day, the situation seemed to worsen. Eventually, United Press International wrote that Ford and Asea Brown Boveri said "there may be a problem with the cells of the sodium-sulfur battery."[15]

For the Ecostar team, the fires were a major blow. Ford was only a few months into the vehicle's evaluation period, and already the cars were being pulled. The company's engineers performed various types of failure analyses—failure mode and effects analysis as well as fault-tree analysis. They examined data from the vehicles' onboard data recorders. And they learned that the failures had occurred within the sealed battery and could have been prevented by better battery control software. Repairs were made and the problem solved, but by that time, it was already too late. The stories were out. And those stories, coupled with the battery's reputation for operating in excess of five hundred degrees, created an impossible situation.

"The press was very interested in EVs at the time," Burba recalled many years later. "And although the problem had been corrected, those two incidents had already created a lot of negative press. In a new technology, that's the last thing you want. If you can't sell a car because people are afraid of it, then it's not a good business decision to invest money in it."

Within Ford, the technology died quietly. In 1995, Ford executives told Burba they would no longer invest in sodium–sulfur. For the company's new electric Ranger truck, they had decided to use a lead–acid battery instead. Lead–acid was better known and better understood. It was less volatile, more forgiving of errors. By midyear, the world knew of sodium–sulfur's demise. "Ford said it chose the lead-acid batteries over the advanced sodium-sulfur batteries, citing the sodium-sulfur battery as too experimental and expensive for early-generation electric vehicles," wrote *American Metal Market*. The publication noted that the choice "was being greeted with confident smiles from the lead-acid battery industry."[16]

But for Burba, it was like losing a friend. At this point, he had spent countless hours with sodium–sulfur. The chemistry was, he thought, a victim of bad press, abandoned too soon. The Ecostar was getting a bad rap, he thought, but there was little he could do. "There was a real disappointment in having to walk away from a six-year effort," he said.

Members of the Ecostar team believed they had failed. Sodium–sulfur had been the future, a potential solution to a rising environmental problem, an answer to California's zero-emission vehicle mandate. With sodium–sulfur, they believed they had had a legitimate chance to create a viable solution, not one that merely met the mandate but one that might actually appeal to consumers. But now it was gone. Worse, it was being replaced by lead–acid, a battery chemistry that had virtually no chance of building a big consumer following. With lead–acid, an EV might have a driving range of forty or fifty miles before needing a multi-hour recharge. Who would pay a premium for such a vehicle?

Ford team members couldn't have known that they had actually succeeded. It was far too early for that. Only history could show that. With their fast-ion science, they had laid the foundation for a new kind of battery. In truth, sodium–sulfur had not been a dead end. Their battery had shown that there was a viable alternative to lead–acid. It had shown how much energy, and how much driving range, was possible with the right chemistry. In that sense, they *had* succeeded.

They just didn't know it yet.

After the demise of General Motors' Electrovette program a decade earlier, Ken Baker had understood the dangers of participating in EV programs. Prior to the Electrovette, Baker had been a rising star within GM. At one point, he'd been the youngest chief engineer in the company.

After the Electrovette program, however, he had become the former head of a defunct vehicle program. His status had fallen. He noticed that he was no longer invited to some of the most important corporate gatherings. In the years afterward, he worked on an experimental sports car for Buick and Oldsmobile, then was transferred to GM's Chevrolet-Pontiac-Canada Group. By the late 1980s, he didn't want to consider any more "innovative duty" on programs that might damage his career, so when he heard rumblings about another electric car project within GM, he ignored them.

"At the time when I was doing the Electrovette, I was concerned that it might be a left turn for me," Baker said later. "So when I heard about the Impact EV, I was skeptical. I didn't want to take a left turn again."

Baker was, by nature, not an "EV guy." He was, in the classic Detroit sense, a car guy. Baker had grown up in central New York state in the small town of Auburn, near Syracuse. His mother had graduated from a small teacher's college known at the time as Potsdam State and, knowing that her son was inclined toward science, had encouraged him to attend Clarkson College of Technology, a little engineering school only a mile or two from her alma mater. Clarkson was in upstate New

York, near the St. Lawrence Seaway, and was mostly notable for its cold winters, prodigious snowfalls, and dearth of female students. There were usually only about fifty women per year among its twenty-five hundred students in 1965, when Baker enrolled there. To find female collegians, Clarkson's male students had to travel the mile or two to Potsdam State, where the majority of students were women. It created for tricky courtship rituals since students often ended up having to walk a couple of miles in below zero weather in order to interact with the opposite sex.

At Clarkson, Baker majored in mechanical engineering. He liked the small school atmosphere, was a member of the intercollegiate lacrosse team, and did well as a student. So it was that in 1969, when the school invited a GM recruiter to campus, Baker interviewed and was offered a job at Buick in Flint, Michigan.

Buick turned out to be a good fit for Baker. He immediately went to work in Buick's engineering department, where he worked with Ed Mertz, later named general manager of Buick, and Lloyd Reuss, who would later become president of GM. By this time, Baker was married and living in Grand Blanc, a suburb of Flint about sixty miles northwest of Detroit.

He loved Buick. There, Baker had opportunities to do the kinds of things he had dreamed about as a budding mechanical engineer at Clarkson. He participated in the design of a concept sports car for Buick-Oldsmobile. He helped with the design of a Buick pace car for the Indy 500. On the side, he even worked on a turbocharged V-6 engine with high school age boys and girls from a local Explorer Post. To his amazement, a version of that engine ended up getting adopted by Buick and placed in production. Later, he joined GM teams that introduced the first reconfigurable touch screen, the first integrated cell phone, and the first digital sound system. By the late 1970s, Baker appeared to be on GM's fast track to management.

That was when he made the left turn to the Electrovette. The Electrovette, a battery-powered Chevy Chevette, had been a GM priority. It was a headline grabber, an honest-to-goodness electric car with a zinc–nickel oxide battery. It had also been a major source of hope for GM's Delco-Remy Division, which was preparing its manufacturing lines to build the zinc–nickel oxide battery. And Baker had been in charge of it all, the youngest chief engineer in the company.

Until he wasn't. The end had come abruptly, the program canceled, when Baker and GM executives had decided the Electrovette was not viable. That left Baker to start his career climb anew.

And now, ten years later, GM's highest-level executives were asking him to do it all over again. In 1987, GM had constructed a car called the Sunraycer for a solar car race across the Australian desert, from Darwin to Adelaide. Sunraycer, a UFO-like vehicle that employed solar cells and batteries, had dominated the race. Afterward, it had been shipped back to the US for a victory lap of sorts, and GM had basked in its high-tech aura while showing it off around the country. But to everyone's surprise, the Sunraycer project hadn't ended in 1987, as expected. It had been so successful that it eventually spawned Project Santana, which had led to Roger Smith's announcement of the GM Impact.

So now, GM was looking for someone to spearhead the Impact project. Baker, with his Electrovette experience a decade earlier, seemed a natural candidate. Lloyd Reuss, who by this time had risen to the GM presidency, made a special point of calling Baker to his office. There, he put on the full-court press, even pulling in new chairman Robert Stempel and vice chairman Bob Schultz to help make the case. It was the ultimate hard sell—the president, chairman, and vice chairman all asking this young engineer to take over GM's newest high-profile project. They even explained that the idea had originated with outgoing chairman Roger Smith. He, too, had wanted Baker. "Lloyd and Bob Stempel and Bob Schultz all convinced me, you're the guy," Baker recalled years later. "They said, 'You've got the vehicle experience and the credentials and we're going to give you unique access.'"

Still, there was the issue of the left turn. Electrovette had seemed important, too, until it suddenly wasn't. Baker had had a decade to consider the failure of the Electrovette. He had thought a lot about it. And he had reached conclusions about what GM did wrong, and what it should do if the situation ever arose again. Therefore, he now proceeded to politely explain those conclusions to GM's highest-ranking executives. If GM was serious, he said, the new vehicle would need a new business model. It would need its own marketing group, its own service group, and its own purchasing group. Moreover, the new vehicle would have to be designed from the ground up for an electric powertrain. He didn't want GM pawning off an existing gas-burning vehicle and then asking him to convert it to electric. He also wanted to have access to the best and most knowledgeable people inside GM. All of these things, he said, would call for a huge investment on GM's part.

Even to Baker it seemed a tall order. To his amazement, however, they listened and quietly nodded their ascent. "They just looked at me and said, 'Let's do it,'" Baker remembered. Thus, in a span of a few hours, Baker had gone from being a man worried about making a left turn to a man who was making another left turn.

A few weeks later, as he stood outside at GM's Milford Proving Grounds, he realized just how scary the project was. When the Impact had been announced at the Los Angeles Auto Show in January 1990, it had basically been a show car. In reality, it hadn't even been designed by GM, but rather by a small West Coast engineering firm called AeroVironment Inc. AeroVironment had a stellar reputation. Its founder, Paul MacCready, would later be named the Engineer of the Century by the American Society of Mechanical Engineers for his development of the human-powered aircraft that flew across the English Channel in 1979. In high-tech circles, his firm was known for having some of the country's most brilliant minds.

But AeroVironment was not an automaker. Its Impact EV was not so much a vehicle as a science project. Yes, it was drivable. And yes, it actually demonstrated a battery-only driving range of 120 miles. But in reality, the range figure had been horribly misleading; it had been based on compromises that would never be made in a consumer vehicle. First and foremost of those was the battery operation—it had been completely discharged in tests. This, of course, would not work in daily practice. Any battery discharged to such a level would be lucky to last a few cycles, and would then have to be quickly replaced. In everyday driving, depth of discharge would be no more than 80 percent, which meant that a production vehicle would immediately lose 20 percent of its capacity, or about twenty-five miles of its publicized range. Then there were the other matters: to boost range, AeroVironment engineers had removed the mirrors, taped the seams of the windows and doors, and eliminated the seals from the wheel bearings.[17] They had employed a fiberglass frame and a fiberglass body, failed to add a heater or air conditioner, and designed the vehicle with only about five inches of clearance above ground level. Finally, the Impact had virtually no suspension and used low-weight motorcycle calipers for its brakes. When Baker added it all up, he concluded that the Impact would be lucky to get 70 miles on a charge.[18]

Clearly, this was a challenge. Cutting the range from 120 miles to 70 miles made a world of difference in terms of marketing and sales. Gasoline-powered vehicles of the day typically drove three hundred to four hundred miles between fill-ups. And the fill-ups took only five to ten minutes, not hours, as they would with the Impact. Moreover, there was the issue of cost. Lower sales meant fewer economies of scale for batteries and other key parts.

One such part was the inverter—the electronic device that converted Impact's DC current from the battery to AC current for use by its motor. Impact's inverter had been a work of art, a genuine breakthrough. It had been designed and built by a brilliant but free-spirited outside engineer named Alan Cocconi. Cocconi's inverter was what separated the Impact from the golf cart reputation that dogged all EVs for decades. It made it possible to use an AC motor to power the wheels, and the AC motor was what gave the Impact its extraordinary acceleration. In that sense, Cocconi's inverter was one of the keys to the whole program, but the problem was that it cost $100,000. One of Baker's first tasks would be to find a way to cut that figure down from $100,000 to less than $2,000.[19]

Still, Baker was convinced the Impact was doable. His strategy as its new program manager was to optimize everything GM knew about cars, and diminish the influence of everything it didn't know. The things it knew were in the area of vehicle engineering. Its engineers knew how to boost efficiencies, how to reduce a vehicle's drag coefficient, how to make lightweight aluminum frames and bodies, and how to use low-rolling-resistance tires. This, Baker believed, was what GM needed to do—make a vehicle so light, so nimble, and so fuel efficient that it would have an acceptable all-electric range, no matter what battery chemistry was employed.

The battery chemistry, however, was the part of the equation that GM didn't know. By 1991, there were many chemistries in existence. GM itself had tried some of them. It had used zinc–nickel on the Electrovette and silver–zinc on the Electrovair. It had even tried hydrogen fuel cells on the Electrovan. And there were other solutions being employed by competitors: Ford was experimenting with sodium–sulfur; Chrysler with nickel–iron. Moreover, new chemistries were appearing on the distant horizon—nickel–metal hydride and lithium-ion were coming up fast.

But in order to "minimize what they didn't know," Baker intended to use lead–acid. Lead–acid was well understood. It had been around for more than a century and was forgiving of abuse. True, its range was limited and its cycle life was downright poor. Drivers of the Impact would need to replace the battery pack every couple of years, at considerable cost. But that's where the other part of Baker's plan came in. Baker's idea was to form a battery consortium that would include other American automakers and would allow its members to share their knowledge and their research on advanced batteries. In a strict sense, it sounded a little bit like a violation of federal antitrust laws, but it wasn't. Until a new technology was commercialized, antitrust laws allowed for a certain degree of collaboration.

"I went to the board and said, 'Let's establish a United States Advanced Battery Consortium, bringing GM, Ford, and Chrysler together with the government to do research on promising battery technologies,'" Baker recalled. "And the board said, 'What the hell would we do that for? Why would we share anything with Ford and Chrysler?'"

Baker, however, prevailed. He explained that their research funding would be tripled by collaborating with Ford and Chrysler, and then it would get another monetary bump from the US government. Moreover, GM would still have a big edge on its competitors, he said. Foreign automakers—Toyota, Nissan, Volkswagen, Daimler, BMW—would not have access to the consortium's research, since the research would hopefully be funded in part by the US Department of Energy. In that sense, American companies would have a "favored nation" status. Most important, he said, GM would still have an edge on Ford and Chrysler by virtue of the Impact's design. The Impact, he said, would be designed from the ground up for superior efficiency, whereas any new EV from Ford or Chrysler would most likely be a conversion—a vehicle originally designed to run on gasoline.

Ultimately, the GM board acquiesced. On January 30, 1991, GM, Ford, and Chrysler signed an agreement to collaborate on advanced battery research.[20] Eight months later, the US Department of Energy joined the effort, agreeing to match funds invested by the Big Three automakers.[21] Now, every dollar GM invested in the consortium was multiplied by six. Within a few months, the consortium set up a plan to invest in short-term, mid-term, and long-term technologies, enabling member companies to gradually climb the learning curve while they learned about batteries.

Surprisingly, the three giant corporations and their government sponsor moved quickly. On May 19, 1992, the United States Advanced Battery Consortium (USABC) announced via satellite transmission that it was awarding a contract for $18.5 million for its mid-term battery. The battery chemistry, called nickel–metal hydride, came as a surprise to many who had expected a more conventional choice, such as nickel–cadmium. Nickel–metal hydride was a relative newcomer to the battery scene. By this time, it was starting to serve in laptops and camcorders, but it hadn't yet been seriously considered for anything as large as a vehicle. An offshoot of the Cold War, it employed an odd alloy of metals that included titanium, vanadium, zirconium, and nickel.

More disturbing, at least for some, was the corporate recipient of the $18.5 million contract. The Ovonic Battery Company was not a major player. It was not an established name, like Eveready, Saft, or Sanyo. Many in the battery industry hadn't even heard of it. Ovonic was located in Troy, Michigan, a suburb of Detroit, and was a subsidiary of a company called Energy Conversion Devices Inc. (ECD), which was mostly notable for losing money over the previous thirty years.

Still, the US Department of Energy seemed pleased. "Ovonic is a small company whose expertise and innovation can help sustain the nation's technological leadership," noted J. Michael David, assistant secretary of conservation and renewable energy.[22]

The company's CEO, Stanford R. Ovshinsky, was, of course, ecstatic. "We have more than fifty people now working on EV battery technology, but we expect that number to double over the next few months," Ovshinsky declared.

So it was that Ovonic's battery took its place as the newly designated chemistry of the future. All that remained was to find out why.

For Stanford Ovshinsky, the designation of nickel–metal hydride as the mid-term battery was a huge victory, and not just in a monetary sense. Ovshinsky did, of course, need the funds. Since his company's founding in 1960, it had always seemed to be on the brink of financial disaster.

But this victory was more than a matter of money. Ovshinsky and his wife, Iris, had launched the company thirty-two years earlier in a Detroit storefront with the idea of "using science and technology to solve the world's societal problems."[23] The company, they said, would be guided by their progressive values. They were decades ahead of America's environmental movement. As early as 1960, Ovshinsky considered hydrogen to be the key to solving the world's energy problems, and he had begun devising a system he called the hydrogen loop for use in fuel cells. In the 1980s, he patented an idea for mass-producing solar cells. And in 1986, he patented the concept of the commercializable nickel–metal hydride battery. He quickly saw it as a potential replacement for oil.

Ovshinsky was, in many ways, the consummate independent inventor, sent straight from central casting. His wild curly hair and effervescent enthusiasm completed the picture of the brilliant, slightly eccentric scientist. Those who knew him best considered Ovshinsky to be a modern-day Edison. Like Edison, he was a man who developed his own ideas and then sold them to industry. And like Edison, he had collected a prodigious number of patents—more than four hundred by his career's end. Also like Edison, he had little formal education, having ended his academic career after graduation from high school. Despite his lack of formal education, however, those who met him were always astonished by the breadth of his scientific knowledge. His inventions ranged from machine tools to automotive components to electronic devices to materials with unique molecular structures. In an era when educational credentials were paramount in the scientific community, Ovshinsky was a man from some previous century, an anathema to many of the highly degreed scientists who considered him an uncredentialed competitor.

Stanford Robert Ovshinsky was born in 1922 in the poorest section of Akron, Ohio, to two working-class Lithuanian Jewish immigrants who knew the sting of anti-Semitism. From a very early age, he had shown signs of scientific curiosity. At age three or four he jumped from his home's second floor window with an open umbrella, expecting to float to the ground, and nearly killed himself.[24] At another point, he almost electrocuted himself after poking a finger in an electrical outlet while trying to see how electricity worked. He also dismantled nearly all of his family's appliances, again due to his determination to understand their inner workings.

Reading, however, may have been his greatest passion. From an exceptionally young age, his precociousness was well known to those around him, and eventually to others in his neighborhood. At age six or seven, he began visiting the library regularly and taking out books on topics ranging from history to astronomy to art. Although the local library had a two-book limit, it changed its rules for the youngster, allowing him to take out whatever number of books he desired. Biographers Lillian Hoddeson and Peter Garrett later wrote that an Akron librarian asked, "Stanford, what will happen to you? When you grow up you'll have read all the books."[25]

By age eight, he already identified himself as a democratic socialist and would argue politics with the men at the barber shop at the end of his street. At some point in his youth, he became active in the Young People's Socialist League with the idea of making "a better life for working people."[26] There, he routinely formed friendships with individuals a decade older than himself.

Still, the promising young student did not go on to college. His parents, he said, wouldn't have stood in his way, but they wouldn't have encouraged it either, thinking it "peculiar."[27] Instead of college, Ovshinsky gravitated toward machine tools. Machine tools were a vital cog in the Akron industrial community, which included such manufacturers as B.F. Goodrich, Goodyear, Firestone, and other rubber companies. They were also a good starting point for an ambitious youngster with a desire to work in industry. While still in high school, Ovshinsky launched his career at a little machine shop called Akron Standard Mold, serving as an apprentice. There, he filed, swept the floors, and changed the drive belts. It was a beginning. He impressed his bosses and earned a written recommendation from a crusty factory foreman, which would help him when he finished high school. In 1941, he applied for a job with B.F. Goodrich, where he was flatly told, "We don't hire Jews."[28] Undeterred, he pulled out his written recommendation and convinced Goodrich to hire him. Later, he said that his jobs at Goodrich and at Akron Standard Mold had provided him with the determination to "become a great machinist."

It could have easily ended that way, with Ovshinsky growing into a respected machinist in a thriving industrial economy. But his intelligence and ambition prevented him from being satisfied with such a life. Ovshinsky's mind was always working, trying to find a better way to do whatever he was doing. His essential interest was in automating machinery. In 1954, he launched the General Automation Corporation with his brother, Herb, in a tiny storefront in Detroit. There, his ideas for "smart machinery" began to bloom. He patented an automatic tractor,[29] an automated power steering system, an automated braking system, an electromagnetic clutch for vehicle transmissions, a high-speed semiconductor switch, and a programmable automatic lathe (at a time when few even knew what the word "programmable" meant). He worked on numerous "cybernetic components" to help automate vehicles, and even wanted to put "sensors all over your car," thirty years before it became commonplace.[30]

Still, Ovshinsky was a magnet for skeptics. His raw ambition, his penchant for exaggeration, and his lack of education would always make him a target. In November 1968, a front-page story in the *New York Times* announced his discovery of a glassy amorphous material that, it was said, could lead to ultrafast electronic switching devices that would outperform transistors.[31] The *Times* reporter who wrote the story had scrupulously sourced it and had included opinions from revered scientists. But it didn't matter. Within days, other scientists began weighing in. Most had never heard of amorphous materials, loosely defined as substances with disordered molecular structures. Those who were vaguely familiar with amorphous materials called them "dirt." They concluded that the story, and the claims within it, were blasphemous. Thus, ECD's stock, which had first soared, collapsed virtually overnight.

"The scientific community was rightfully skeptical," noted Dr. Hellmut Fritzsche, a University of Chicago physicist who served on the board of Ovshinsky's company. "Those materials and their properties could not be looked up in any reference book. No one knew anything about them."[32]

But in the years following Ovshinsky's announcement, his ideas were validated. English physicist Sir Nevill Mott later received a Nobel Prize for his work in amorphous materials and credited Ovshinsky in his acceptance speech. Two decades later, amorphous materials would become a key element in fax machines, portable computer displays, photovoltaic devices, and computer memories. Still, Ovshinsky's reputation as a self-aggrandizer would continue to dog him, and his company would always struggle. In the years between 1960 and 1990, profits were almost nonexistent. "There may have been one or two years where we made money during that time, but no more," he told the *Chicago Tribune*.[33]

In that sense, the nickel–metal hydride battery was different. It offered commercial possibilities, which was critical for a man whose company always seemed to be on the verge of collapse. But it was also the culmination of a dream. Since founding the company in 1960, he and his wife Iris had repeatedly discussed ways to improve the environment. They were very much alike—both scientists, both trusting and open, and both highly idealistic. Iris was also as much a political radical as Ovshinsky, having been raised by parents who were self-described anarchists, both of whom rejected the ideas of religion, property, and government.[34] Together, over the years, the two had formed a pact to find alternatives to oil. Therefore in 1981, when the company found the new battery chemistry, Ovshinsky was quick to identify its importance. He had finally discovered a way to get rid of oil.

In truth, Ovshinsky himself did not make the breakthrough discovery. By this time, his company had grown. It employed dozens of PhD-level researchers. One of the researchers, an Israeli electrochemist named Arie Reger, was the first to notice in late 1981 that a combination of elements that included Ovshinsky's disordered amorphous materials might serve as a battery electrode. In experiments, the new electrode stored hydrogen. He reported it to colleagues, who concurred. At this point there was no real battery—only a beaker of liquid containing a nickel-based cathode and the new material.[35]

But it worked, and Ovshinsky was quick to recognize what his team had found. In February 1982, he proudly demonstrated the new "battery" at a weekly team meeting. The demonstration was vintage Ovshinsky—a tiny electric toy fan wired to two metal electrodes sitting in a beaker of potassium hydroxide solution.[36] The anode materials—vanadium, zirconium, cobalt, manganese, aluminum, and iron—had been salvaged from scrap. The cathode had been taken from a nickel–cadmium battery purchased at Kmart.[37] Still, the fan turned. It was enough for Ovshinsky, and it led him to predict that this battery would one day power an electric car. As work progressed, he compared it to existing lead–acid batteries and declared it would offer twice as much energy. Thus, the company set about to apply for patents. Ovshinsky soon learned that his company wasn't the first. Others—General Electric and Phillips Corporation—had invented similar batteries a decade earlier. But it didn't matter. Ovshinsky viewed his as different. "All of the previous attempts to utilize hydrogen in secondary batteries have proven to be unsuccessful, because the crystalline materials have one or more limiting factors which prevent commercialization," the company wrote in its patent application.[38] "The invention herein provides a new and improved battery having an electrode formed from disordered non-equilibrium material which does not suffer from the disadvantages and limitations of the prior art."

Therein lay the difference. Ovshinsky's battery was *commercializable*. The patent was granted on November 18, 1986.

By that time, Ovshinsky was supremely confident. He had already spun out a subsidiary, called the Ovonic Battery Company, to produce his new product. The product was called the nickel–metal hydride battery. He launched the subsidiary early in 1983 with a few scientists who were reassigned from ECD. In the beginning they built lab prototypes, but that soon changed. By 1987 they'd created a small production line. Then on September 13, 1988, everything changed. Ovshinsky signed an agreement with Hitachi Maxell Ltd. of Japan. In return for the right to market nickel–metal hydride batteries, Hitachi paid $1 million and granted ECD the right to use Hitachi's production technology. Hitachi also kicked in an extra $400,000 for a 5 percent stake in Ovonic Battery Company.[39] The signing attracted little to no media attention. But it didn't matter. Finally, the struggling inventor was on the verge of major commercial success.

After that, everything was a blur. Nickel–metal hydride was a hot commodity in the technology world. One of Germany's biggest battery manufacturers, Varta AG, bought a license. It was followed by Gold Peak Industries Ltd. of Hong Kong. Then the flood gates opened: Duracell, Gates Energy Products, Matsushita Battery, Mitsubishi Materials, Nippon Storage Battery, Sanyo Electric, and Toshiba Battery jumped into the market. To be sure, not all paid for licenses, which would later lead to litigation. But the electronics market wanted nickel–metal hydride and wanted it immediately. Motorola announced that it would use nickel–metal hydride in its cell phones. Compaq, Digital Equipment, and Dauphin Technology put nickel–metal hydride in their notebook computers. Even Hyundai Motor Company signed a licensing agreement, announcing that it planned to use the new chemistry to build an electric car with a 220-mile driving range.[40]

By 1992, the rest of the world had begun to recognize the emergence of nickel–metal hydride. A prescient article in the trade publication *American Metal Market* noted accurately that nickel–metal hydride was eyeing "nickel-cadmium's battery turf." Nickel–cadmium, it said, was about to lose a big chunk of its market share.

A month later, the United States Advanced Battery Consortium announced it was awarding $18.5 million to Ovonic Battery Company for the development of an electric car battery. Now, nickel–metal hydride had arrived. The pressure was on Ovonic Battery not only to deliver a better battery but to help make the electric car competitive. "We need a breakthrough in battery technology," Chrysler's Bob Davis declared at an EV seminar. "We're all counting on the USABC."[41]

With that, Ovshinsky slipped into public relations mode. With the press now aware of his company, he grabbed every opportunity to promote it. For Ovshinsky, it was a natural step. Because he didn't have the luxury and the guaranteed salary of a professorship, he was always ready to put on his sales hat. And in 1993, that's what he did. He told *Mechanical Engineering* magazine that his batteries would take the GM Impact 240 miles, then said the number would jump to 300 with a few advancements.[42] He wrote a letter to the *New York Times*, expressing dismay over a reader's negative opinion of electric cars. There, he again promoted his company, stating his battery "permits a range of 250 to 300 miles, lasts the car's lifetime, has the power to accelerate the sportiest automotive models, recharges in fifteen minutes, uses environmentally safe materials, is easily manufactured, and has a cost in production that allows the car's operation at one-third a gasoline's engine."[43]

His promotional efforts were often shameless. He courted the press, learned the first names of reporters, and even called their homes, sometimes at odd hours.[44] He hawked his products and pushed his company, offering exclusives to media outlets willing to tell his story. In some ways, his efforts paralleled those of Thomas Edison, who had always preferred talking to the press rather than making speeches at scientific conferences.

Ovshinsky believed that his tactics paid dividends. In April 1993, his company received a $1.4 million purchase order from the USABC for prototype vehicle batteries.[45] Ovshinsky immediately turned around and put that money to work, fashioning a battery pack for Chrysler's TEVan. The TEVan was an electrified minivan that used nickel–iron batteries (like those made by Thomas Edison eighty years earlier). Ovshinsky wanted to prove that his batteries were better than nickel–iron, so he persuaded Chrysler to lend him a van and proceeded to replace the nickel–iron pack with nickel–metal hydride. In the summer of '93, Ovshinsky demonstrated a working prototype of his battery in the TEVan. Then, true to form, his company quickly batted out a press release,[46] and a local newspaper ran a story, along with a picture of Ovshinsky, smiling proudly with the minivan. It was again vintage Ovshinsky. He had failed to tell anyone about his plans and then had publicized his work.

The USABC, which had wanted to control all press, was enraged. The last thing it wanted was to tip off the Japanese, or worse, to convey the idea to the California Air Resources Board that automakers were farther along than they really were. As the USABC saw it, Ovshinsky was providing inappropriately rosy results. He exaggerated the driving range of the batteries and rarely mentioned the fact that the cost of manufactured batteries might be astronomical. His letter to the *New York Times* had been a case in point. He had described driving ranges of 250 to 300 miles and recharge times of fifteen minutes. Virtually no one in the auto industry believed those numbers. Within a year, Chrysler engineers would learn how horribly inaccurate they really were. After testing nickel–metal hydride in a minivan for months, Chrysler vice president François Castaing told the *Times* that his engineers were getting about 100 miles of range, not 250 miles, and recharge took eight hours, not fifteen minutes. Worse, he said, with a heater or air conditioner running, the batteries would be exhausted in 50 miles.[47]

So it was that the USABC's lawyers sent a letter to Ovshinsky, telling him to cease and desist. They reminded him that his company had accepted $18.5 million and that he was required to abide by the rules of the USABC. Ovshinsky was, of course, incensed. As he saw it, the USABC was badmouthing his batteries so it might convince California to lift its EV mandate. He believed himself to be trapped in the middle. He felt his batteries were being sabotaged to make a political point.

The automakers believed, however, that the solution was to find a way to exact more control over Ovshinsky. Somewhat by happenstance, that occurred in 1994. Their solution came in the form of Robert Stempel. Stempel, former CEO and chairman of General Motors, had been relieved of his GM duties late in 1992. In the ensuing year, he had gone through heart surgery and then had bounced back, ready to go back to work. Early in '94, he joined the board of Energy Conversion Devices, where he gradually emerged as an ally and friend to Stan Ovshinsky. Stempel was, in a sense, the perfect complement to the ambitious and unpredictable inventor. Stempel was an engineer who had climbed the ranks within GM by virtue of his technical knowledge and business acumen. He had been involved in the development of GM's first front-wheel-drive cars, its first catalytic converter exhaust systems, and its first computer-controlled ignition systems. Moreover, he *loved* electric cars. Within GM, he was known as the father of the Impact EV. He had encouraged Ken Baker to take the job as Impact's chief engineer. Stempel felt so strongly about EVs that after GM had retired him, he had actually considered finding a way to do the Impact himself. With such an attitude, and with his background, he was a huge help to Ovshinsky. He brought discipline to Ovshinsky's scientific creativity. And he helped Ovshinsky understand GM's position on the California electric car mandate. Stempel hated the mandate. The mandate, he said, was a mistake brought about by Roger Smith's error in going public with the Impact. He had even, quite notoriously, once stated that the California Air Resources Board "didn't know shit about electric vehicles."[48] His beliefs, coming from someone who so loved EVs, served to temper Ovshinsky's viewpoint.

Not long after he joined the board, Stempel brokered a deal between GM and Ovonic Battery. He structured a joint venture, with GM owning 60 percent of the new company and ECD owning 40 percent. It was to be called GM Ovonic. As Stempel saw it, GM Ovonic was an opportunity for him to help Ovshinsky reach his dream. Ovshinsky wanted to put his battery into a production car and the Impact was the perfect candidate for nickel–metal hydride. Both sides would be happy: Ovshinsky's battery would find a home and Stempel would still have a hand in the development of the Impact. The joint venture called for GM to provide the manufacturing and funding, while Ovonic provided the materials and components for the battery.

Thus, the stage was set for nickel–metal hydride to finally make its entrance as the power source for the world's best EV. Moreover, all indicators seemed to be pointing upward for Ovonic's battery. In April 1994, Ovonic's battery powered the winning car in an electric car race in Arizona.[49] The car, called the Solectria Force RS, traversed the 125-mile racecourse without stopping for a recharge. Then, in August, the USABC awarded an additional $5.5 million in funding to Ovonic.[50] Clearly, the stars were aligning. Stempel was on board, he believed in nickel–metal hydride, and he trusted Ovshinsky.

What neither Stempel nor Ovshinsky knew, however, was that another change was coming. It had started bubbling up in Japan a couple of years earlier, with electronics manufacturers clamoring for a new battery chemistry called lithium-ion. *American Metal Market*, which had earlier posted a headline about nickel–metal hydride invading the turf of nickel–cadmium, was now posting a similar headline about lithium-ion invading "nickel-metal-hydride turf."[51] It seemed impossible, but it was true. The brief reign of the nickel–metal hydride battery was already being threatened. And by a chemistry that no one had ever heard of, called lithium-ion. At first, those who knew about lithium-ion had thought it an unlikely competitor in the auto industry. Lithium-ion powered *electronics*. Little devices with wee currents, milliamp-type stuff. Not cars. But in December of 1994 that, too, changed when the USABC awarded $18 million to Duracell Inc. and Varta AG to develop lithium-ion batteries for electric cars.

Now it was official. There was a new battery chemistry on the horizon, and it was coming fast.

The big day for the electric car arrived on January 4, 1996. It was almost six years to the day since Roger Smith had unveiled the Impact in Los Angeles, and in the interim GM had come through and produced an electric car.

In many ways, the event had an air of déjà vu—same time of year, same city, same buzz around it as in 1990. There were more than five hundred reporters in attendance as GM's chairman, Jack Smith (no relation to Roger), made the announcement.

The press, of course, loved the story. It was an actual story, a business story, an environmental story, in an era when automotive journalism was still dominated by gearhead articles. It was so big that CNN decided to cover it live, beaming it around the world to millions of viewers. Over the next few days, the news would reach some ninety-five million people, estimated to be about twelve million more than had watched the previous Super Bowl.[52]

And GM was at the center of it all. Smith told attendees that GM "was the first major automaker in modern times to market specifically designed electric cars to the public." He told them that the car was packed with innovations—plastic body panels, electric brakes, low-rolling-resistance tires, magnesium frame seats, one-piece instrument panels, dual airbags, cruise control, even a CD player. In all, there were twenty-three new patents on it, he said, and it was 60 percent lighter than a comparable gas-burning car. He told them that it would be sold in four Western markets—Los Angeles, San Diego, Phoenix, and Tucson—by the end of 1996. And it had a new name, EV1, which was appropriate given the fact that it was the industry's first purpose-built electric car in decades. Jokes about the Impact and the Ford Whiplash would now disappear.

Smith then topped it off with the best line of the day. "This is not a concept car," he said. "This is not a conversion. This is a car for people who never want to go to the gas station again." For the next few days, the line about the gas station would resonate and be repeated on countless television and radio newscasts, as well as in bars, restaurants, kitchens, and offices. It stuck.

The electric car had finally arrived. It was there to be seen on millions of television screens and millions of newspaper pages, looking like the future of automotive driving. The teardrop-shaped EV1 was low and sleek and environmentally desirable.

For the public, it all seemed so easy. But it hadn't been. The six years since Roger Smith had announced the Impact had been a roller-coaster ride within GM. By 1991, the company's financial problems had grown overwhelming. In that year alone, GM had lost $4.45 billion, closed twenty-one plants, and laid off seventy-four thousand workers. By '92, a disgruntled board had forced out Stempel, who had been the Impact's biggest backer and corporate guardian. All at once, the company abandoned Stempel's baby, jettisoning its production plans and cutting its staff by two-thirds. The message inside GM was simple: There was no longer room for "innovative" programs that couldn't pull their own weight. By year's end, when Ken Baker traveled to Impact's production plant in Lansing, Michigan, to break the bad news to workers, he was booed.[53]

Still, somehow, the Impact survived. With the program seemingly on life support, GM had allotted Baker $32 million to build fifty test vehicles, and he had built the test vehicles, then used thirty of them to provide two-week test drives to consumers in twelve cities. In Los Angeles, more than ten thousand consumers signed up. All at once, the corpse began breathing again. In 1994, Baker, working with Stan Ovshinsky, outfitted an Impact with a nickel–metal hydride battery pack. True to form, Ovshinsky predicted it would travel 200 miles on a charge and, to everyone's surprise, it actually did. On the very first try, it went 201 miles.

Suddenly, the Impact came back. In Lansing, the spirit returned. When the manufacturing group started preparing to build production cars, team members bonded to each other, and to the idea of building a real electric car. When Baker would travel to the Lansing plant in the evenings, he found people working late—not just the hourly workers who were paid overtime but the salaried people as well. They didn't want to leave work; they had more to do. Baker found himself sending people home at night, telling them to see their families and get some rest. As Baker sensed the growing feeling of commitment, he instituted new ideas and work practices. "We had Friday 'win meetings,'" he said. "We'd get together and say, 'What was your big win this week?' and then we'd all cheer." Late one Friday afternoon, team members called him to Lansing to deal with an "emergency." It was his birthday, and he wasn't anxious to drive the ninety miles to Lansing because he had dinner plans, but he did it to deal with the emergency. When he arrived, he found the team gathered in a conference room, where they pulled back a curtain, revealing the first completed production vehicle with a giant red ribbon around it. Serial number one. They knew it was his birthday, and they wanted him to see their accomplishment. Thirty years later, he would still choke up when recalling it. That, he said, was the day when the team really bonded. He would never again worry about the Impact being a left turn for his career.

Still, the Impacts were not ready to compete with gasoline-burning cars. The big problem was still the battery. GM engineers didn't believe that Ovshinsky's battery was ready for a production vehicle, and so they opted for the old standby, lead–acid. That, however, was a weak solution. A lead–acid battery pack would offer about forty watt-hours per kilogram and *might* get a seventy-mile range, largely based on the lightweighting work done by the engineering team. Worse, lead–acid had poor cycle life. The owner would have to replace the pack every twenty thousand to thirty thousand miles, at considerable cost. And if the owner kept the car for a hundred thousand miles, there would be at least three replacements, and possibly four or five. For that reason, GM decided to lease the vehicles rather than sell them. Under the leasing arrangement, GM would provide a free pack whenever a new one was needed.

Weak as it was, however, lead–acid was still better than nickel–metal hydride. As far as GM engineers were concerned, nickel–metal hydride was still a journey into the great unknown. The big issues were life and cost. Stan Ovshinsky had claimed his battery could live for ten thousand cycles. One cycle translated to charging and discharging the battery one time. As such, ten thousand cycles would be an amazing feat. But Ovshinsky's claims, while technically accurate, had been based on flashlight cells. GM engineers learned, to their dismay, that bigger cells were living for five hundred cycles, not ten thousand. And modules—small groups of batteries—were living for two hundred cycles. Worse, the cycle life of an entire pack was fifty to one hundred cycles.[54]

Cost was equally intimidating. Engineers estimated that the cost of one battery pack came to about $15,000. And that was just for the cells. The entire pack, which included the cells, electronics, modules, and cooling system, was about $5,000 more, bringing the grand total to about $20,000. GM could not go to production with those kinds of costs. At least not yet.

So it was that when Jack Smith announced the rollout of the EV1 on that January day in Los Angeles, the car still had a lead–acid battery pack. In the beginning, however, the world didn't seem to care. The *New York Times* described it as swift, silent, and vibration-free. "It is almost as different from an internal combustion car as a computer is from a typewriter," it wrote.[55] Writers also marveled at the fact that there was no oil, air filters, spark plugs, or fan belts to change. *Motor Trend* cited its aluminum frame, plastic body panels, and drag coefficient, which was 30 percent less than any car on the market.[56] By the end of the year, just as some of the novelty had started to wear off, GM delivered EV1s to twenty-four Saturn dealerships in Arizona and California, and the buzz began anew. Celebrities, including former *St. Elsewhere* star Ed Begley Jr. and *Baywatch* star Alexandra Paul, leased vehicles, causing another little publicity blitz.

Still, GM engineers knew the honeymoon wouldn't last forever and so began laying plans to swap the lead–acid battery for nickel–metal hydride. By early 1997, nickel–metal hydride had benefited from years of engineering attention, and the company believed the costs and cycle life were under control. Thus, in April of 1997, Jack Smith made another announcement: GM would offer a nickel–metal hydride battery in its next generation of EV1s. The new battery, he said, would double the car's range.

Ken Baker liked that. "That makes the EV1 the undisputed leader in range and performance of any electric vehicle in the world," he said.

When the end appeared on the horizon for the EV1, it was not a surprise. Not really. The program had nearly died in 1992, then had been resuscitated. But now, executives inside the company were complaining about it again, the way it was draining cash. It had bled nearly a billion dollars over a decade, and its lease numbers had been so tiny as to be virtually nonexistent. Yet when the end actually came, General Motors seemed unprepared.

No one had expected the emotion that surrounded its demise. First, there was the mock funeral. Fifteen people, including actor Ed Begley Jr. and a little-known California director named Chris Paine, conducted the small funeral for the EV1 at a Beverly Hills cemetery. It had seemed a tad melodramatic. Then there was the round-the-clock vigil at a GM training center in Burbank, California. EV1 lessees set up an outpost of folding chairs. They gathered in rotating four-hour shifts, sticking with it through long hot nights and torrential downpours. They carried signs saying, "GM make a U-turn" and "Sell the EV1 for scrap." Sometimes they staged rallies, with as many as a hundred people showing up. When flatbed trucks had rolled up to haul away used EV1s from the building's parking lot, the enthusiasts tried to block the way. At the same time, a group of electric car buffs launched an Internet website called dontcrush.com, urging big automakers (not just GM) to sell their remaining EVs, rather than flattening them. After a while, the emotion ceased being a surprise.

Word trickled back to Detroit, leaving engineers scratching their heads, while simultaneously filling them with pride. They knew they had built a good car, given the obvious challenges. An amazing car. "People threw themselves over their hoods rather than give them up," EV1 project team leader Ken Baker recalled years later. "They loved them."

But the end had been a visible and real possibility for years, delayed only by the CARB mandate. In the beginning, CARB had demanded that 2 percent of all vehicles sold be zero-emission, rising to 10 percent by 2003. CARB's board members had guessed that the mandate would scare automakers into some level of compliance, and they were right: The automakers were terrified. Then in October 1991, the situation had actually grown more serious, when nine northeast states, acting as a bloc, had also voted to adopt the mandate. Section 177 of the federal Clean Air Act allowed them to do so—they could either conform to federal EPA standards or adopt California's law, there was no in-between. So the nine states, including New York and Massachusetts, were now going to have a Zero Emissions Vehicle (ZEV) mandate, or so they thought.

Thus began a decade-long battle between California and the automakers. It had been difficult enough when automakers were told to produce and sell EVs in California. California was a huge market; it represented maybe a tenth of the vehicles sold annually in the US. But the nine northeast states, plus California, represented much more than that. For GM, 40 to 50 percent of its North American market was now at risk. Worse, electric cars were unlikely to perform well in cold northeast climates. Batteries would lose range even on good days. And the use of cabin heaters and defrosters would cause yet another problem. Therefore, the automakers felt they had to fight. For California, which truly had a serious environmental problem, the addition of the nine northeast states was a curse. It made the battle much more difficult and uglier. Lawyers took over, with the tussle moving from court to court.

While the legal fight raged, however, engineers at all the big companies continued to work on electric cars. Ford had its sodium–sulfur Ecostar, followed by its Ranger EV pickup. Chrysler built the EPIC electric minivan. Honda had the EV Plus; Toyota, the RAV4 EV; Nissan, the Altra EV. GM actually had two—the S-10 electric pickup and the EV1. All, save the EV1, were conversion vehicles—that is, vehicles with the guts ripped out and replaced by batteries. The batteries were generally lead–acid or Stan Ovshinsky's nickel–metal hydride. Only Nissan made the daring move to lithium-ion.

At GM, however, the grim realities had settled in. Yes, the decision to go with a purpose-built design yielded a better vehicle, but the costs were astronomical. The first fifty EV1s, which had been hand built, cost between $350,000 and $500,000 apiece.[57] Later that number dropped to $250,000 as manufacturing and minor economies of scale kicked in. Yet, GM executives found the market to be soft. Consumers were not beating a path to their door. Whereas the car had initially been leased for $530 a month, the company found itself dropping the rate to $399 to attract more customers.[58] "A percentage of customers didn't buy because they said it was too costly," a GM spokesman explained to the *New York Times* in 1997.[59] Saturn dealerships, which were the marketing arm for the EV1, reported that they leased just 175 of them in the first five months of 1997. It was an absurd situation—here they were, leasing a quarter-million-dollar car for $4,800 a year, and saying that they were still struggling to find customers. For the moment, however, GM wrote it off as the cost of building a market for a new, unproven technology.

In the courts, the story grew immensely complicated, but the essential facts were these: In 1996, California officials voted to water down the mandate, rescinding the requirement that called for 2 percent of vehicles sold to be electric by 1998.[60] Initially, they left intact the requirement for 10 percent of vehicles to be electric by 2003. But a few years later, that, too, was dropped, replaced by a complicated point system that called for a combination of hybrids, plug-in hybrids, and pure EVs.

Thus, the sense of urgency began waning. Moreover, the media honeymoon was also ending. Whereas journalists had initially gushed about the EV1, reality started setting in during 1997. "As good as the EV1 is, when fully charged it has the equivalent energy of only about a gallon-and-a-half of gas on board—past the point in most cars when the little fuel-gauge flashes in a panicky thirst," wrote *Motor Trend* in one review. "If the EV1 runs out of zap, it's gonna take hours to get the silent creature charged. If a tire blows, Wal-Mart doesn't stock the exotic 50-psi Michelins the EV1 requires. And if something breaks, you'd better pull into a major university's electrical engineering department. For those reasons, merely driving the EV1, as comfortable and satisfying as it is, is a true adventure."[61]

In an attempt to reverse the slide, GM had announced at the 1998 Detroit Auto Show that it would replace EV1's lead–acid battery with nickel–metal hydride. Engineers said that nickel–metal hydride would double the car's range to about 160 miles. The announcement's timing was good, arriving at a moment when the initial media buzz was just beginning to drop off. The EV1 Gen II, as it was called, received another round of press coverage that the other electric competitors couldn't seem to get. Stan Ovshinsky added to that press coverage by announcing that his

Ovonic Battery Company planned to boost its battery production with a new plant in Kettering, Ohio. The plant, he said, would produce battery packs for twenty-five hundred electric cars per year.

Still, the press coverage didn't translate to sales. In April 1999, *Automotive News*'s "tote board" reported that GM had leased a grand total of just 600 vehicles in its first two years, and competitors were leasing even fewer.[62] Toyota had leased just 507 RAV4 EVs. Ford had 500, Honda, 300, and Nissan had leased just 30 Altra EVs.

Early in 2000, the inevitable started to happen. The press began its death watch after the EV1's production line in GM's Lansing plant was removed to make room for the assembly of the Cadillac Eldorado. By 2001 the news became official. In 2002, GM shocked EV1 owners by announcing that it would end the leases of EV1 owners. It wanted its cars back. Worse, none of the EV1's lessees had the option of buying their cars.

Even Ken Baker, who'd led the EV1 program through its best and worst moments, was unable to buy a car. He had hoped to purchase serial number 1, the car that had been presented to him a few years earlier, adorned by a red ribbon. "They told me, 'We're not going to sell the cars to anyone,'" he said years later. "They said they were going to crush the cars, except for a very few. And those cars were going to be sent to museums."

Indeed, they were sent to museums. Epcot at Walt Disney World in Florida received one for display, as did the R.E. Olds Transportation Museum in Lansing, Michigan, and the Electric Vehicle Information Center in Chattanooga, Tennessee, among others. A few were sent to museums overseas. The only fully intact EV1 (serial number 660) went to the Smithsonian Institution in Washington, DC. Baker never learned where his serial number 1 car ended up.

In March 2005, the *Washington Post* reported that most of the remaining cars were taken by flatbed truck to a GM facility in Mesa, Arizona, where they were crushed. Although GM assured lessees that the cars would be put to use by researchers, a former EV1 driver named Kenneth Adelman obtained aerial photos proving that the cars were "meeting their demise there."[63]

GM, of course, had its reasons for not selling the EV1s to lessees. The company said it was not willing to maintain a parts supply and service infrastructure for the fifteen-year minimum required by the state of California. It said it couldn't provide service because many of the suppliers quit making the two thousand unique parts that went into the design.[64] In a sense, GM had become trapped by its own desire for innovation. Unlike the Ford Ranger EV and the Toyota RAV4 EV and the others, the EV1 had been purpose-built. It was too good, too unusual. GM executives knew that. And given the opportunity, they also knew that collectors would keep it alive for decades. They compared it to the Corvette: In 2013, sixty years after the Corvette's birth, approximately 88 percent of Corvettes *ever made* were still out there, in one form or another. GM executives were proud of the Corvette's legacy, but at the same time they didn't want to be building battery packs and inverters for the EV1 sixty years later.

Whether those reasons were sufficient for crushing the EV1 was another matter. In retrospect, virtually everyone at GM understood how bad the optics were. The 2006 film *Who Killed the Electric Car?* proved, if nothing else, what a monumental public relations blunder the crushing had been. It spawned dozens of conspiracy theories, turning the death of the EV1 into the auto industry's version of the Kennedy assassination.

GM executives recognized that. In 2006, former GM CEO and chairman Rick Wagoner acknowledged that the axing of the EV1 had been the worst decision of his tenure. "It didn't affect profitability," he told *Motor Trend*, "but it did affect image."[65] Two years later, he repeated the statement to National Public Radio.

Had the battery been ready, had it offered low cost and high energy, all of that might have changed. On the whole, most GM engineers subscribed to that theory. They believed that chemistry, not conspiracy, brought down the EV1. "I didn't ever feel there was a conspiracy," Baker said many years later. "I wouldn't have worked that hard if I did, and I couldn't have inspired others to work that hard. But a better battery would have been another matter."

7

The Lithium-Ion Car

When Lance Atkins joined the Nissan Altra team in California, he considered it a perfect assignment. Atkins was young—just four years out of college—and wanted to be part of the auto industry. But he liked living in California, which was hardly a hub for young engineers hoping to design cars. Moreover, he wasn't willing to move to Detroit.

Fortunately for Atkins, fate intervened. While studying mechanical engineering at California State University, Fresno, in the early 1990s, he had participated in the Sunraycer solar car event. It was a good learning experience for him, a catalyst of sorts. It helped him realize that Detroit wasn't the only place to work on cars. "It dawned on me, seeing all the news on electric vehicles and solar cars, that, 'Hey, wait a minute, here's an activity that's car-related and seems to be happening in California,'" he said many years later. After graduation, he landed a job with a little start-up called Pacific EV, which was doing contract research work for various entities, including the US Defense Advanced Research Projects Agency (DARPA). After four years of battery and electric vehicle (EV) research, he moved to Nissan. The timing was perfect—Nissan just happened to be launching a new electric vehicle called the Altra EV at its US headquarters in California.

The Altra EV was a good fit for someone with Atkins's background. It was scheduled to be the world's first lithium-ion-based production car. In 1998 no one knew who would buy it, how they would use it, or whether it would fulfill their needs, so Atkins's job was to help Nissan understand the answers to those questions.

The car itself had already been designed in Japan. So had the battery. Starting in 1994, Nissan had teamed with Sony to create lithium-ion cells for an EV battery pack. Up to that time, Sony had mostly manufactured the finger-sized 18650-style cylindrical cells, which were used in camcorders and cell phones. But Sony's engineers were surprisingly well attuned to the needs of Nissan. Although it wasn't well known, Sony had actually built electric cars in its past. Indeed, the company's archives contained a photo of a very young Yoshio Nishi riding in the passenger seat of an experimental car powered by a zinc–air battery as far back as 1971. So Sony was ready and willing to collaborate with Nissan. It did so, and in the process delivered a cell of a radically different size. The cells were jelly rolls—that is, wound and cylindrical. But they were enormous—each about sixteen and a half inches long and two and a half inches in diameter. No one had ever seen lithium-ion cells like these. Nissan engineers planned to wire eight cells together into a module and then place twelve modules into each car's battery pack. Thus, the car would be powered by ninety-six cells.

When it arrived in the US in 1998, the Altra EV seemed to have materialized from out of nowhere. It was a new electric car, slated for a very small production run, with a lithium-ion battery containing John Goodenough's lithium cobalt oxide chemistry, seen previously only in laptops and phones. The automotive press viewed it as a science experiment and was mostly indifferent to it. The first batch of news stories about the Altra were inconsequential, and no one in Detroit paid much attention to them.

Still, the Altra was much more than a science experiment for the engineers at Nissan. Though few people in Detroit knew it, Nissan had a long, rich history of building electric cars. Its experience with EVs dated all the way back to 1947 with a car called the Tama. It had followed the Tama with other EVs in 1959, '70, and '73. In 1985 it created one called the Resort EV, for resort hotels, and followed that in the '90s with the President EV, the Cedric EV, and the Prairie Joy EV. It even produced an electric garbage truck. In 1991, it rolled out a car called the FEV-I (for Future Electric Vehicle) that used nickel–cadmium batteries. Then, at the Tokyo Motor Show in 1995, the company made a bigger move toward electrification. It debuted another concept car called the FEV-II, which used Sony's large-format lithium-ion cells. The FEV-II was a four-seater that looked a little like a Volkswagen Beetle, and Nissan built only one. But that one reportedly offered about 120 miles of driving range, an unmatched figure at the time.

When Nissan subsequently decided to bring the Altra to the US a couple of years later, it had hoped for media traction. The Altra was an answer to the California Air Resources Board's EV mandate, so Nissan made the announcement in California. More, it announced its intention to build the Altra the day before the unveiling of GM's EV1 in January 1996 in an attempt to steal some of GM's thunder. But the strategy hadn't worked. No one was stealing GM's thunder. GM's EV1 was an actual car, whereas Nissan's announcement was about an intention to offer an EV in '98. The media was more interested in real cars than in promises.

Two years later—January 2, 1998—Nissan rolled out the actual vehicle at the Los Angeles Auto Show. For the media, it was still uninspiring. The Altra was essentially a four-seat minivan—a *mini*-minivan—and minivans were judged as dowdy by the automotive press. It didn't compare favorably with the racy-looking EV1. And the first "production run" consisted of just thirty vehicles. Nissan carefully selected the Altra's early customers—some were Nissan employees and others were fleet customers.

Altra was basically a research and development vehicle, which is where Lance Atkins fit in. His job was to study how the customers used the vehicles—how often they drove them and how hard they pushed them. Each vehicle was equipped with a data recorder under the carpet beneath the driver's seat. Atkins would visit each car every month, remove the flash card from the recorder, replace it with a fresh one, and then study the data.

Atkins was especially interested in the Altra's lithium-ion battery. He wanted to know how it responded to real-world use—its charging and discharging characteristics, what would happen when it was pushed, and what would happen if it was overcharged. In some cases, by comparing battery data to GPS data, he learned that some of the cars were actually recharging as they made short downhill trips, thanks to Altra's regenerative braking system. In other cases, he noticed the opposite—some drivers found themselves unable to keep up with traffic during steep uphill chugs because battery power dwindled on climbs. Overall, however, lithium-ion was generally deemed successful. It was powerful and offered impressive range. Nissan had considered other chemistries, including nickel–metal hydride. But Nissan engineers had thought nickel–metal too lacking in energy density, and therefore too heavy. So they had decided to go with the riskier choice—lithium-ion—and now they were learning that their decision had been the right one.

The lithium-ion battery was in most ways considered an engineering triumph, but it still had its issues. It offered three times the energy density of a lead–acid chemistry, and 50 percent more energy than nickel–metal hydride, but it was exorbitantly expensive. Published estimates placed the pack cost at roughly $100,000 apiece, and there were whispers that it had actually cost Nissan more. That, of course, wasn't a figure that Nissan could live with in the long run, and engineers needed to find ways to chop it to a manageable level.

One of the big cost problems was the production of the large-format cylindrical cells. Nissan engineers could have reduced that dramatically if they had chosen to use little 18650 cells, of course, which were already being produced in massive volumes by Sony for camcorders, laptops, and cell phones. Instead, they worked with Sony to build the large-format cylindrical cells, which were almost a foot and a half long. The special run had cost them dearly. But they were convinced they needed "cell-to-cell balance"—that is, uniform voltages for each and every cell they placed into the vehicle. Their fear was if one cell was out of balance, it would affect the recharging process and ultimately ruin the capacity and life of the pack. Therefore, little 18650 cells were regarded as impractical. Given the fact that they would have needed to string thousands of little cells together, it seemed inevitable that a few cells would be out of spec.

Thus, they had chosen to make the cells as big as possible. Fewer cells, fewer problems. Then, they meticulously checked the voltage of each of their ninety-six cells. "I can remember being somewhat surprised when I came to Nissan and heard about the battery management system for the Altra, and realized they were controlling the voltage of each cell down to the millivolt (thousandth of a volt) level," Atkins said years later. "They had this really high-precision system to keep all the cells matched up. Trying to do that with thousands of little cells would have required a massive piece of electronics." Atkins had learned from previous experience on DARPA projects that such systems simply didn't exist at the time, at least not as off-the-shelf products.

So it was that Nissan selected the big, expensive cells. To keep costs down, its engineers built a relatively small pack that offered a 120-mile driving range, even though they could have built a bigger one, which they believed would have boosted the range to 200 miles. Nissan manufactured thirty vehicles to start. The cars served mostly in utility companies, at places like Southern California Edison, Pacific Gas & Electric, and the Los Angeles Department of Water and Power. The Santa Monica Police Department employed a few Altras as meter maid cars, and a few more were briefly rented out at LA International Airport. The rest ended up in the hands of Nissan employees.

Media coverage was scant, but the few publications that wrote about the vehicle seemed impressed. An environmental publication called *Green Car Journal* test-drove the Altra at Nissan's Tochigi track in Japan and noted that the "test drive proved the Altra EV to be quite a capable performer, with good acceleration and handling characteristics. In fact, no shortcomings were detected other than some slight gear whine."[1]

Mostly, though, national newspapers ignored it. The Altra was considered by most to be something of a specialty vehicle, in the category of a growing number of cars from Chrysler, Ford, Honda, and Toyota that were rolling out in 1998 as a means of addressing California's Zero Emissions Vehicle (ZEV) mandate. The fact that it used lithium-ion meant little. The big story was still GM's EV1.

Nissan, however, was seeing what it needed to see. It laid plans to build two hundred more Altras. The next batch of vehicles used a slightly different flavor of the lithium-ion chemistry—Goodenough and Thackeray's lithium manganese oxide spinel—as a means of reducing cost. For engineers, the results seemed promising.

No one fully understood the significance yet, but the lithium-ion car was on the horizon.

The need for a better lithium-ion battery was not lost on the battery community. Since the mid-1990s, battery scientists in universities, government labs, and auto companies had been accelerating their battery development efforts. The automakers who did not have their own internal efforts were teaming with outside battery manufacturers.

Two new battery chemistries from the mid to late 1990s would later emerge as leaders for the auto industry. Both came from scientists whose names were familiar to the community. The first chemistry was called lithium iron phosphate, developed in the laboratory of John Goodenough. By that time Goodenough had left Oxford, not because he wanted to but because Oxford had retired him in 1987 when he had reached the mandatory retirement age of sixty-five. Goodenough hadn't liked the idea; he wanted to keep working. He loved his research, but equally important, he didn't know if he had enough money to fund his retirement. Oxford had a formula for determining a pension—years of service, divided by eighty, multiplied by final salary. In Goodenough's case, it meant one-eighth of his final salary, an amount that he considered "meager."[2] Thus he began talking with people at the University of Texas in Austin. "I was delighted to be able to come back because I wasn't quite sure how I was going to retire on five thousand pounds a year," he later said.[3]

The move to Texas was another unusual tale in the Goodenough saga. The job opening at the University of Texas was not in chemistry (his Oxford background) or in physics (his PhD studies), but rather in engineering. More specifically, it was in materials science, which at the University of Texas came under the heading of mechanical engineering. Thus, he would be a professor of mechanical engineering. The reaction at the school was not unlike the one at Oxford many years earlier, when he had become chair of the school's Inorganic Chemistry Laboratory, despite the fact that he was not a chemist. Now, he was becoming an engineering professor, despite not being an engineer. "The dean of engineering said, 'But he's not an engineer!'" Goodenough recalled. "And, of course, he was right. But I was elected to the [National] Academy of Engineering at the same time he was." Thus, Goodenough became an engineer. A University of Texas engineer. The university needed a world-class material scientist and Goodenough was exactly that.

It didn't take long before Goodenough's presence started to produce results. Shortly after his arrival, he brought over a promising young postdoc from Oxford named Arumugam Manthiram. Manthiram had done his doctoral dissertation in India on polyanion oxides and, together with Goodenough, he began toying with the idea of using them as an intercalation compound. Soon afterward, Goodenough and a young Indian postdoc named Akshaya Padhi took the polyanion idea a step further, discovering that they could insert and extract lithium from a combination of iron and phosphorous. Gradually, it dawned on them that they might have stumbled upon another lithium battery cathode.

Lithium iron phosphate was a beautiful solution in many ways. Its main advantage was that it was cobalt-free. Thus, it was far cheaper than Goodenough's earlier cathode, lithium cobalt oxide. It was also environmentally preferable and eliminated the human rights concerns that accompanied cobalt mining. The only problem was that its electrical conductivity was poor. And the poor conductivity made Goodenough question its viability in the marketplace.

Unexpectedly, though, Michel Armand stepped in. By this time, Armand was working at the University of Montreal. Paging through some conference proceedings during 1997, he stumbled upon an abstract for an upcoming paper written by Goodenough. The topic of the paper was the lithium iron phosphate cathode. As it turned out, Armand had also been working on lithium iron phosphate for about six months, unsuccessfully. "When I saw that John Goodenough had succeeded, I said, 'This is the compound I've been looking for,'" Armand recalled later. "So immediately after reading the abstract, I called John and said, 'I'm taking the first flight out and I'm going to offer you a collaboration.'"

When Armand arrived in Austin, however, Goodenough delivered a surprisingly negative assessment of his new battery. "He said, 'I don't believe in this compound,'" Armand recalled later. "'It's not going to work in a battery. It's got a very compact lattice and it's not electrically conductive.'" Armand, however, was insistent. On the flight back to Montreal, he did some back-of-the-envelope calculations and concluded he could get it to work. Upon his return to Montreal, he started working on a carbon coating for the lithium iron phosphate cathode. With sponsorship from the Canadian electric utility, Hydro-Québec, he learned that a thin layer of carbon made the material more conductive. Quickly, the University of Montreal and Hydro-Québec filed for a patent on the carbon coating. And within a year, they entered into a business arrangement with the University of Texas to license Goodenough's new cathode.

To be sure, the new material didn't have the same high voltage as lithium cobalt oxide. It didn't have the same energy or power. But it worked well with the electrolytes of the day. And it didn't have cobalt. Hydro-Québec viewed it as a battery for grid storage—that is, storage of utility electricity. Used in large volumes, it offered the potential for greater use of solar or wind power. Moreover, Hydro-Québec engineers believed it could serve in some electric car applications, especially in low-cost EVs that didn't need long driving ranges. "Even if we assumed that it could be used in just 2 percent of the cars in the world, it was still worth enough to make you drool," Armand said.

Now there were three cathodes.

The other promising battery chemistry of the era was called nickel manganese cobalt, or NMC. Like lithium iron phosphate, it was the product of familiar scientists—Mike Thackeray, who had codeveloped the lithium manganese spinel cathode, and independently Jeff Dahn, who had earlier uncovered the value of the EC (ethylene carbonate)-based electrolyte.

By the time Thackeray had begun to work in earnest on NMC, he had moved to the US. After his earlier development of lithium manganese oxide spinel at Oxford in 1982, he had returned to the Council for Scientific and Industrial Research in Pretoria, South Africa. But when CSIR announced it was shutting down its lithium battery programs, Thackeray left for Argonne National Laboratory outside Chicago. It was a major uprooting. By 1994, he and his wife had three daughters, aged fifteen, twelve, and nine. The girls had grown up in South Africa. Chicago was nine thousand miles from their home and they knew no one there. What's more, Thackeray's wife, Lisa, an adult literacy teacher, faced the prospect of restarting her career in a foreign country with no professional contacts. To top it all off, they arrived in February and faced a ferocious winter of the kind they'd never seen in Pretoria.

Still, Argonne itself was a good fit for Thackeray. About a year after he arrived, Thackeray started to work with a colleague, Chris Johnson, to design a new layered electrode material. It was the beginning of NMC. Thackeray and Johnson quickly learned that NMC offered potential advantages over John Goodenough's lithium cobalt oxide chemistry. It had good stability, allowing more lithium ions to be extracted. Whereas lithium-ion batteries with Goodenough's lithium cobalt oxide cathode could shuttle maybe 50 percent of their lithium ions back and forth, NMC could shuttle at least 60 percent. More, it could do so while employing less cobalt.

Still, the NMC work done by Thackeray and Johnson in the mid-1990s wasn't always a high priority. It often took a back seat to some of Argonne's industry-supported projects. But in 2000, that changed. At a conference in the Alpine city of Como, Italy, Thackeray listened as another scientist, Brett Ammundsen of Pacific Lithium in New Zealand, presented a paper on a material that was eerily similar to his NMC. Although it wasn't exactly the same as NMC, it was an unsettling experience for Thackeray. "It was a trigger for me," Thackeray said later. "Suddenly, I knew that there were other people working in our patch. I called Chris Johnson and said, 'We've got to get our data together and file immediately.'" And that was exactly what they did. Three weeks later, Thackeray and Johnson filed for a US patent.[4]

The benefits of NMC weren't earthshaking. But NMC brought a new level of stability, which translated to safety. It delivered slightly better energy capacity. Possibly better power. The big message, however, was that it reduced the amount of cobalt in the battery. Whereas Goodenough's lithium cobalt oxide cathode was 100 percent cobalt, NMC contained approximately one-third cobalt. And that would be music to the ears of automakers, mainly for cost reasons.

What Thackeray and Johnson didn't know, however, was that they weren't alone in their pursuit of NMC. It was another of those ideas in the air. In the fall of 2000, Jeff Dahn made his entry into the world of NMC cathodes. Dahn, who by this time was a professor at Dalhousie University in Canada, attended an Electrochemical Society meeting in Phoenix. During the course of the conference, Dahn had an experience that was amazingly similar to Thackeray's. He watched as a scientist from Pacific Lithium in New Zealand (again) delivered a paper about lithium chromium manganese oxide. After the conference, on the bus ride back to his hotel, Dahn and one of his postdocs discussed the paper and scratched their heads. "We said, 'This doesn't make any sense, but if you look at it a different way, it does make sense,'" Dahn recalled later. "So we said, 'You can do this with nickel, manganese, and cobalt, and it should work like a charm.'" Dahn later applied for an international patent on his version of the NMC chemistry.

But as much as Thackeray had been unaware of Dahn, Dahn was unaware of a third party in Japan working on NMC. The third scientist was Tsutomu "Tom" Ohzuku at Osaka City University, who would file for patents around the same time as Dahn, as would Brett Ammundsen of Pacific Lithium.

So now there were four versions of NMC, each marginally different than the other. But even as those evolved, the battery community was forging ahead with a wave of other new chemistries, including one that would later have huge impact on the auto industry (at a yet to be formed company called Tesla Motors).

It was called lithium nickel cobalt aluminum oxide (NCA), and its development was clouded in secrecy. It had started as lithium nickel oxide. But when lithium nickel oxide was found to be inherently unsafe, scientists had begun looking for ways to combine it with some other element that would boost its safety. Tom Ohzuku was one of the first to make headway with it. He suggested that aluminum be added to improve its safety. Around the same time, others suggested that cobalt be added to improve its cycle life. The ongoing mystery, however, was who had decided to combine all three of the elements in NCA. But someone put them all together and, in the end, it worked and produced very high energy.

So now there were five different lithium-ion cathodes. Originally there had been lithium cobalt oxide (Goodenough), then lithium manganese spinel (Thackeray and Goodenough), then lithium iron phosphate (Goodenough, Padhi, and Armand), then NMC (independently, Thackeray, Dahn, Ohzuku, and Ammundsen), and finally nickel cobalt aluminum (Ohzuku). The fact that there were now so many spoke volumes about the changes going on in the battery industry. Two decades earlier, John Goodenough had pleaded with battery manufacturers to merely *consider* his lithium cobalt oxide, only to be ignored. Moreover, he had asked his employer, Oxford University, to fund a patent and had been told that Oxford did not involve itself in intellectual property matters.

Such was not the case in 2000, however. Universities now had tech transfer offices to facilitate patenting and licensing. They were prepared to circle the wagons around their intellectual property. Thus, in the case of NMC technology, inventors and licensees—including Argonne, 3M, BASF in Germany, and Umicore in Belgium—began lining up against one another in legal disputes over ownership. They were disputes that no one could have dreamed of two decades earlier because, back then, no one had cared. Moreover, the legal disputes were not confined to NMC. Around the same time, the University of Texas and Hydro-Québec squared off against an MIT spin-off called A123 Systems LLC over infringement of their lithium iron phosphate patent. It was a far cry from Goodenough's pioneering days. Now, there was money involved.

Indeed, the potential for profit was now staggering, and much of that potential lay within the auto industry. Argonne would go on to score big via a licensing agreement with Korean battery maker LG Chem, which was teaming with General Motors. GM would later employ NMC in a plug-in hybrid called the Volt and in an all-electric car, the Bolt. Meanwhile, lithium iron phosphate would start slow with grid storage applications but would eventually graduate to EVs in a big way with the Chinese manufacturer BYD Auto Company Ltd. Finally, Tesla and Panasonic would turn NCA into an industry unto itself.

To be sure, there were many miles to go in 2001. It was always a challenge to take a battery chemistry and transform it into a usable product for the auto industry. It never, ever went as smoothly or as quickly as the world imagined. And every new innovation was always heavily scrutinized and understandably viewed with skepticism. Patience would be key.

Still, three new lithium-ion chemistries had arrived, and they were there for the taking.

From the beginning, no one at Nissan expected the Altra EV to be a long-term production effort. Initially, Nissan built thirty of them as a research and development project in 1998. The key was the Sony–Nissan lithium-ion battery, which used John Goodenough's lithium cobalt oxide cathode and a soft carbon anode. The chemistry performed surprisingly well, but the battery packs cost more than $100,000 per vehicle, and Nissan engineers wanted to launch another small production run in an effort to test a less expensive chemistry.

In 2000, the company built thirty more, this time using a Thackeray–Goodenough lithium manganese oxide (LMO) battery from Shin-Kobe Denki. Unlike GM, Nissan was able to do its work under the radar, being spared national media attention. The automotive trade journal *Automotive News* noted that cost concerns had forced Nissan to change its battery chemistries,[5] but consumer publications were virtually unaware of the Altra and so did not cover it. There was no worldwide live satellite coverage of its unveiling, no stampede of reporters, as there had been for the EV1, and that worked to Nissan's advantage.

In 2002, Nissan rolled out two hundred more Altras powered by Thackeray's lithium manganese oxide (LMO) chemistry. Over time, Nissan engineers learned that the LMO technology was cheaper than but didn't perform as well as lithium cobalt oxide, especially in terms of battery life. Gradually, they tweaked the chemistry and changed the physical format of the cells.

In 2005, satisfied with what its engineers had learned, Nissan shut down its Altra program. It was that simple. The company had learned what it needed to know about lithium-ion. At the time, Nissan USA was moving its US headquarters from California to Tennessee, so it called its California-based lease customers, most of whom were utility companies and employees, and ended the leases.

The cars were returned with no fanfare—no vigils, no signs, no Hollywood stars, nor protests. There was no hint to the huge successes that lay ahead.

Nissan knew what it needed to know in order to move forward. "We were able to say, 'Now we understand these vehicles,'" said Atkins of Nissan. "We could figure out how to roll them out as large-scale products."

Nissan now had bigger plans for the lithium-ion battery.

Even as Nissan laid plans for its lithium-ion car, the auto industry was in the midst of a particularly dark public relations moment. Much of it still centered around General Motors. After heavily publicizing its electric car, GM had turned around and crushed it. It had snapped up its cars from unsuspecting lessees, then lied about the crushing, telling the public that the remaining vehicles would be used for research purposes. They weren't, of course. Whether GM had good reasons for discontinuing the EV1 didn't matter. The optics were terrible.

Then they got worse. In 2006, all the makers of electric cars, not just GM, came under heavy political fire. The problem was that they had chosen to kill off their electric cars at a moment in history when public opinion seemed to be reversing itself. Suddenly, there was a growing awareness of a climatological phenomenon called global warming. It had begun in earnest in 1988, at a hearing of the House Committee on Natural Resources in Washington, DC. On a steamy day in June of that year, James Hansen, a researcher for the National Aeronautics and Space Administration (NASA), had testified before the committee, declaring that there was a "strong cause and effect relationship" between climate and human alteration of the atmosphere. It was a wonderfully theatrical moment that evolved into a huge news story, carried not only in the US but around the globe. Within days, a CNN poll showed that a majority of Americans now believed that the drought of 1988, which was scorching prairies and farmlands across the country, was directly related to carbon dioxide emissions. The changing of American opinion had begun, if only in a small way.

Now, eighteen years later, after GM had crushed the last of its EV1s, the idea of global warming had had time to simmer. More mainstream Americans were now aware of it. Then in 2006, two films took the public discussion to new level. In June, former vice president Al Gore produced *An Inconvenient Truth*, which made a strong case for the dangers of global warming and described the situation as "a planetary emergency." The film won an Academy Award for Best Documentary Feature and, ultimately, a Nobel Peace Prize for Gore. Then, five weeks after its debut came another mainstream documentary, *Who Killed the Electric Car?* by director Chris Paine, which laid the public's growing climate fears at the doorstep of the auto industry. *Who Killed the Electric Car?* was most notable for its retelling of the EV1 crushing, but it also made an important link to global warming. Gasoline cars, it said, were adding nineteen pounds of carbon dioxide to the atmosphere every time they burned a gallon of gas. And carbon dioxide, it said, was the foundation of global warming. "We've got the equivalent of a nuclear time bomb on our hands with global warming," an engineer named S. David Freeman said in the film.

Within the auto industry, there were two distinctly different reactions to the growing crisis. The first was from the engineering ranks. Automotive engineers in general had heavy scientific grounding, especially in areas of applied physics (including thermodynamics and fluid mechanics), but many were nonetheless skeptical about climate claims. Some believed in global warming, some doubted it. But it didn't matter whether they believed or not. Most still saw the automotive world in the traditional way—consumers bought vehicles based on a combination of cost, performance, luxury, and styling. They did not purchase vehicles based on politics, Hollywood narratives, or climate. Thus, there were no internal discussions about building an electric car to save the world. For most, such thinking was outside their purview anyway. "Global warming was not on the table then," said physicist Frank Jamerson, who had been a key member of GM's early EV teams, and who had served as a member of the United States Advanced Battery Consortium. Most automotive engineers, he said, believed that the electric car in itself would not curb global warming anyway. The battery wasn't ready, the infrastructure wasn't ready, and more than half of US electricity came from the burning of coal in 2006, which meant that electric cars would essentially be powered by fossil fuels anyway. So they considered the EV mostly a symbolic solution.

The other reaction came from the automotive public relations departments and, by extension, the manufacturers' executive committees. Most of the PR professionals saw it as a massive public relations problem. Almost all of the automakers had big teams of public relations people—usually dozens of them—whose job it was to make their employers look good. Looking good meant not only writing press releases about new vehicles but churning out stories to show what good corporate citizens their bosses were. The PR people would write about the industry's donations to charities, to educational foundations, and to the causes of the underprivileged and the environment. The stories appeared first on the manufacturers' websites and occasionally were picked up by industry publications. Ultimately, those stories gave the impression that the manufacturer was not only successful but was a caring community member as well. Yet here was *Who Killed the Electric Car?*, showing a very different picture. Big flatbed trucks, cruising down the interstates, carrying crushed electric cars. Helicopter shots of auto graveyards with flattened EVs piled high atop one another. Seeing the visuals, much of the public bought into the film's conspiratorial undercurrent, which suggested that the auto industry had colluded with oil companies, knowingly killing off a viable technology. The film lent credence to the idea that automakers were participating in an industry-wide cover-up. For the PR staffs, the optics of it were beyond terrible—it was the kind of publicity that their worst enemies could not have dreamed up.

And it wasn't just GM and the EV1. On *Late Night with David Letterman*, movie star Tom Hanks talked about his beloved RAV4 EV, lamenting over Toyota's decision to kill it off. When asked why he drove an EV, Hanks responded, "I'm saving America, Dave. I'm saving America by driving an electric car." Letterman's young audience members cheered, applauded, and laughed. To some degree, they knew Hanks's comment was tongue-in-cheek. But here was Hanks, an American pop culture icon, figuratively saving the world, even as Big Auto appeared to be counting its billions. It couldn't have looked worse. The auto industry's public relations community was mortified. It was a clear sign to them that the ground was shifting beneath their feet.

Gradually, auto industry executives came to understand the immenseness of their mistake. Whether or not they saw it as a "planetary emergency" was not the issue, per se. To them, the issue was public image. Crushing the cars had been a colossal blunder. Former GM chairman Rick Wagoner would later describe it as the biggest mistake of his career.

Thus, it dawned on auto executives around the world that there was a lesson to be learned. There was still support for the electric car. The electric car was, if nothing else, a sign of the times, one they would be unwise to ignore.

8

Electric Salvation

In the late summer of 2003, Tom Gage did not sense that the auto industry might be on the verge of change. Gage had worked in the industry, and he knew that the big automakers considered electrification to be a waste of time and money. Worse, the mainstream manufacturers—General Motors, Ford, Toyota, Honda, Chrysler, and the rest—were now abandoning their electric car efforts. GM's EV1, the most famous of the bunch, was being very publicly and painfully scrapped.

Still, on this particular day in September of 2003, Gage had taken his company's little yellow two-seat electric car to the California Speedway in the town of Fontana, about forty-five miles east of Los Angeles, to prove a point. The speedway had a big new two-mile oval track with capacity for about 120,000 spectators and a beautiful view of the San Gabriel Mountains in the distance. Despite the dwindling support for electric cars, he had brought his company's car, called the Tzero (pronounced "tee-zero"), to this speedway for a demonstration.

Over the previous few years, word about the Tzero had trickled out to electric car enthusiasts and to a few journalists. The Tzero, it was said, could beat any gasoline-burning car in a short race. The list of racy muscle cars—Lamborghinis, Ferraris, Porsches, Dodge Vipers—vanquished by the Tzero was long and growing. A few of the cars had quarter-million-dollar price tags. For the losers, it was always frustrating. They took their expensive performance cars to remote airport runways and various other venues, only to lose to this . . . *enviro-mobile*. One Lamborghini owner had insisted on numerous rematches, and had kept "slipping" his clutch as a way of boosting acceleration—finally burning out the clutch.

But on this day, Gage was not so confident. He wasn't sure what his car would do. The Tzero of the last few years, the one that had beaten car after car, had just undergone a big change. The car's owner, AC Propulsion Inc. of San Dimas, had switched its power source. Instead of the lead–acid battery pack that had powered it for the last few years, the Tzero was now using a new chemistry called lithium-ion. More, it was employing a whole new type of pack. Instead of twenty-eight big twelve-volt cells, AC Propulsion was using tiny laptop cells—sixty-eight hundred of them. The cells, finger-size batteries known as 18650s, looked like conventional AA batteries. They were wired together in modules with sixty-eight cells per module. Then one hundred of the modules were linked into one big pack.

It was the type of arrangement that no one in Detroit—or anywhere else in the auto industry—would have taken seriously. Nissan had been using lithium-ion for at least eight years at this point and had never dared to try anything so radical. Each of Nissan's cylindrical cells was sixteen and a half inches long and two and a half inches in diameter. Fewer cells, fewer problems was the way Nissan engineers looked at it. And the engineers of Detroit, without ever bothering to say so publicly, agreed. This was not the sort of thing a big automaker would do.

Gage knew what mainstream automakers thought. A fifty-three-year-old former race car mechanic, Gage had spent more than half a lifetime working on cars. He had started his professional career working for Bob McQueen, a former two-time national champion in SCCA (Sports Car Club of America) racing. He had owned two businesses, had served eight years as an engineer for Chrysler Corporation, and had spent another eight years developing electric cars for AC Propulsion. He was bright and loved cars. And he also happened to have a mechanical engineering degree from Stanford University and an MBA from Carnegie Mellon Institute, which meant that he could put himself in the place of a corporate engineer. He was so plugged in that he could predict, almost word for word, what a Detroit engineer would say about the Tzero.

But on this particular day, the scenario was different than it had been for the previous four years. The new Tzero was only one week old. They'd been working on the lithium-ion version of the car for six months, had just finished a week earlier, and hadn't really had time to work all the bugs out. Moreover, today's activities were somewhat public. Mark Vaughn, an editor from *AutoWeek* magazine, would be there. He was bringing two vehicles to the track with him. The *New York Times* was also planning a story on the Tzero. And, curiously enough, Tony Shalhoub, star of the cable TV series *Monk*, would also be there. Shalhoub, who owned a Toyota RAV4 EV, was an enthusiast who had heard about the Tzero. He was among a growing number of EV buffs who wanted to see the little yellow racer for themselves.

Gage's one source of confidence was his company's track record. Racers, engineers, editors—all had initially doubted the Tzero, and then had invariably walked away awestruck. It went without saying that AC Propulsion knew something about electric cars that few others knew, and that was largely due to the brilliance of the company's founder, Alan Cocconi. Cocconi was a skinny, wavy-haired Cal Tech graduate who looked like the nerdy scientist played by Harold Ramis in the movie *Ghostbusters*. Many believed he'd been the real innovator behind the GM EV1, even though he hadn't been on staff at GM. He'd been a contractor, a technical consultant of sorts. But even at GM, his reputation had preceded him; he was known all the way up to the CEO level. It was Cocconi who had designed the inverter that enabled the EV1 to use an AC motor. It was Cocconi who'd blessed the EV1 with its extraordinary acceleration. And it was Cocconi who'd turned a kit car into the Tzero, enabling it to out-accelerate virtually any performance car in the world. And now, Cocconi believed that his new Tzero, with its lithium-ion batteries, was even faster than the original.

As it turned out, Gage had little reason for concern. "We did some acceleration runs and the car was fantastic," Gage recalled years later. In a slalom test, the new Tzero outperformed a Mercedes-engineered Chrysler Crossfire and a Scion xA that Vaughn had brought to the track. It turned a 4.1-second zero-to-sixty time, which was very good, but Gage believed there was still room for improvement. The suspension hadn't yet been properly calibrated and it needed better tires. In truth, they hadn't even scratched the surface of its capabilities yet. Shalhoub took the car around the track and came back thrilled. He compared it to a ride he'd once taken in a navy Blue Angel jet. "I thought I was at the top end," he told the *New York Times*. "Then I stepped on it a little more and it doubled in speed. It's terrifying, but it actually handles beautifully."[1]

Over the next few days, Gage and Cocconi worked on the new lithium-ion car and learned just how much room they still had for improvement. The new battery weighed five hundred pounds less than the original, and its traction control and handling hadn't even been calibrated for the lighter weight. After a few tweaks, it turned a 3.6-second zero-to-sixty time. What's more, they learned that it was capable of driving three hundred miles on a single charge. Now, they believed they had the holy grail of electrification—range and acceleration.

Better yet, the word was out. They received a big thumbs-up from *AutoWeek* and from the *New York Times*. The *Times* described the Tzero's acceleration as a "jaw-dropping, stomach-clenching and near-terrifying blur."

Another nonbeliever had been won over.

Tom Gage had been a car nut for as long as he could remember. As a child, his parents had always been amazed to find that he could identify various vehicles more than a half mile down the road. From that distance he not only knew the manufacturer; he knew the model and the model year. He could, for example, tell the difference between a 1959 Chevy Impala and a 1959 Chevy Bel Air from a half mile away.

Gage grew up in Champaign, Illinois, not far from the main campus of the University of Illinois. His father was a professor of educational psychology at the university and his mother was a housewife who was active in social issues such as racial integration and nuclear test ban treaties. Gage was twelve years old when his father was offered a professorship at Stanford University, and the family picked up and moved to Palo Alto.

The move had little effect on Gage's interest in cars, however. In high school, he was working on vehicles before he had a driver's license. As soon as he reached driving age, he bought a beat-up British sports car, an Austin-Healey Sprite. The Sprite was a little, low-cost open two-seater about which was said, "A chap could keep it in his bike shed." In an era when hot-rodders prided themselves on their modified Chevies and Fords, Gage was the only one in his school to own a Sprite.

Soon after getting a driver's license, Gage and his friends began going to local tracks to take in the races as spectators. They first got to know the tracks around Northern California—including Laguna Seca Raceway, Cotati Speedway, and Vaca Valley Raceway. Later, they started jumping on the interstate to take in races in Southern California, particularly at Riverside International Raceway. They loved it, living the life of hot-rodders; it was a life straight out of *American Graffiti*.

When it came time for college in 1968, Gage enrolled in mechanical engineering at Stanford. Hot-rodding, however, wasn't the lifestyle of choice for students at Stanford in 1968. Stanford was a hotbed of anti-war activity. Souped-up British race cars and mechanical engineering degrees were part of another era, and Gage felt a little out of step with the campus. Even his engineering professors saw the world differently than he did. "I remember talking to my advisor and saying, 'I wish there was some stuff in the curriculum about cars,'" he recalled many years later. "And he sort of huffed and puffed and said, 'Well, this isn't vocational school.'"

But Gage's enthusiasm for cars was undeterred. Shortly before he graduated from Stanford, he began sending letters to racing teams around the country. Soon, he heard back from Bob McQueen's racing team in Atlanta. Upon graduation, he packed up all his worldly possessions in a used BMW sedan and set out for Atlanta. "I'm sure my parents weren't pleased," he said years later. "But they didn't put up a fuss."

For the time, it was an amazing move. In the early 1970s, American corporations couldn't seem to find enough engineering graduates, and salaries for new grads were high. But McQueen's racing shop wasn't paying Gage big money. It wasn't even hiring him as an engineer. He was essentially a mechanic, making roughly minimum wage. "I would have worked for free," Gage said. "I was in heaven, going to races all over the country and working on race cars."

Indeed, the job was a paradise for Gage. He would travel as part of a caravan to races, then go back to Atlanta on weekends and take care of customer cars for well-heeled racing enthusiasts. His main job was to "de-smog" street cars (the Datsun 240Z was particularly popular) for owners who didn't like the new emission control devices that were being strapped onto engines of the day. At the time, catalytic converters didn't exist, and automakers tweaked emissions with bell cranks and pulleys that would limit the idle speed. "It was pretty straightforward," Gage said. "We'd stick BBs in the vacuum lines and remove some of the contraptions that were bolted to the engines." The modified cars were dirtier, of course, but performed better.

Gage spent three years working for McQueen before starting his own shop with another of McQueen's mechanics, Tom Wyatt. In their years working for McQueen, the two Toms had built up an impressive knowledge of turbochargers, and they had therefore decided to open a shop that would specialize in turbocharger installation and repair. They called it Turbo Toms'.

Turbo Toms' was another three-year paradise for Gage. He liked modifying cars, boosting their performance. Mostly, his customers owned Datsuns, BMWs, and offbeat, non-Detroit cars. His job was to take their engines apart and put turbos on them. After three years, however, he began to feel antsy again. He still hadn't worked a real engineering job. He wondered what it would be like to work a corporate job and to earn an engineer's salary. He thus applied for a job as a mechanical engineer with a subsidiary of United Technologies, a tier-two automotive supplier in Pittsburgh that manufactured emission controls equipment. Gage spent two years there before the company was shut down. Once again, he found himself looking for work.

He opened another turbo shop in Pittsburgh before thoughts of an actual engineering career again invaded his mind. Gage thus enrolled in the MBA program at Carnegie Mellon University. Upon completion, he accepted an engineering job at Chrysler Corporation.

He started at Chrysler in 1984, in the middle of the Iacocca years. At the time, Lee Iacocca was a national figure, having delivered Chrysler from the brink of disaster. The company had rebounded; it was a known for the K-car, a vehicle that was helping Chrysler despite its rather obvious quality shortcomings. But the job there wasn't what he had hoped for. He started in product planning, then moved to regulatory affairs, where he dealt with the growing body of government fuel efficiency and emissions regulations. He ended up making multiple trips to Washington, DC, to support his bosses, who were testifying before Congress. No matter how he looked at it, he couldn't call this an engineering role.

Oddly, the event that began to change Tom Gage was one that didn't even involve him. Chrysler had launched an electric minivan program. The minivan was part of Chrysler's response to the California Zero Emissions Vehicle (ZEV) mandate. It used nickel–iron batteries, which were only slightly better than the nickel–iron cells that Thomas Edison had invented seventy-five years earlier. The van was crude and sluggish; a driver could go deep into the accelerator and still get little acceleration. It was, in a sense, one of the first of the "compliance cars," intended only as a response to the mandate.

One day a friend of Gage's, an engineer on the electric minivan team, was assigned the unenviable task of driving the minivan to Lee Iacocca's house in Bloomfield Hills. Iacocca, he was told, wanted to drive it from his home to Chrysler's Highland Park office the next morning. Gage's friend arrived early the next day at Iacocca's house and handed the keys to the chairman. Riding in the passenger's seat, he watched as Iacocca pressed his foot into the accelerator and reacted to the sluggish way the car responded. Within a minute or two, he could see the dour look on Iacocca's face. And with each passing moment, it grew worse. By the time Iacocca turned the car onto Woodward Avenue for the final run into Highland Park, he was fuming. Unable to keep up with the throng of speeding rush-hour traffic, Iacocca watched helplessly as other auto executives, people he knew, sped and weaved around him. Here was the chairman of Chrysler, the most famous auto executive in the world, the father of the Ford Mustang, putt-putting down Woodward Avenue, angrily hunched over the wheel of a minivan. Gage's friend in the passenger seat shrank down, wondering if he was about to lose his job.

The story evolved into great office fodder, with some engineers gleefully retelling it while the others cowered in fear of the potential consequences. Gage, however, had a different take. He was simply amazed. "That was my first exposure to the reality of it," he said later. "I realized then that the [electric] vehicles were crude and the auto companies were only halfway enthusiastic about them. The engineers working on it were enthusiastic, but management thought it was a waste of time and money."

He placed the Iacocca tale in context against an article he had recently read in the *New Yorker*. The article, "The End of Nature,"[2] had had a profound effect on Gage. It detailed a new phenomenon called global warming, and for the first time in his life, Gage was aware of the environment. "It was eye-opening to me," he said. "Up to that time, my perception had been that we could dump anything into the ocean, or into the atmosphere, and that the Earth was so vast, and we were so puny, it wouldn't make any difference. But now I knew I was wrong."

Twenty years after leaving Stanford, Tom Gage was having his first counterculture moment. He dashed off a strongly worded letter to one his bosses, someone a couple of levels above him. The letter suggested that Chrysler needed to integrate more environmental awareness into its product planning. It needed to take global warming into account as it planned its vehicle lines. There was more at stake here than meeting federal fuel efficiency regulations, or adhering to California's ZEV mandate, he wrote.

It didn't take long before Gage realized he'd made a tactical error. "I wouldn't say they were hostile to the letter," he recalled. "But I knew I'd overstepped my bounds in the way I presented it." The letter brought a certain level of discomfort to all his subsequent interactions with management.

By this time, Gage had spent eight years at Chrysler. It was his longest stretch ever in a job. And now he was uncomfortable again, and the discomfort went beyond his problems with management. He wanted to get back to California. He wanted to see the sun again. In Detroit in winter, he would rise every morning in darkness, drive to work in darkness, and drive home in darkness. For pleasure, he liked to race cars, but the racing season in Michigan was short, May to October at best. But now he was married with a two-and-half-year-old daughter and a second child on the way and therefore needed a good-paying job.

"I looked for a job in California and found one at SRI—Stanford Research International," he said. "They offered to pay for the move, so we packed up and moved out there. It turned out to be a good move."

That was the difference-maker for him, looking back on it.

At SRI, Tom Gage was essentially a consultant. SRI was a nonprofit scientific institute doing research for government agencies and commercial businesses. It had once been part of Stanford University but had split off from it a quarter century earlier. Some of its work was auto related, but most was not. Palo Alto, being twenty-four hundred miles from Detroit, wasn't an automotive hub, and it was sometimes difficult for the company to land automotive contracts.

In 1994, however, SRI signed a contract with Honda Motor Company to do a background study on electric vehicles (EVs)—standard practices, environmental considerations, regulations. Honda also wanted to learn more about the state of the art. It knew that GM was building the Impact, of course, but it knew little about other competitors. Essentially, the company was casting nets, looking for new information. Part of what it wanted to learn was about the blossoming "conversion" scene. California was home to a growing number of small companies that were converting gas-burning cars to electrics.

That's where Tom Gage fit in. Having served in product planning for Chrysler, Gage had been privy to the auto industry's inside view of EVs. He had actually spent time on Capitol Hill learning about state and federal regulations. He knew the terrain. One of his first duties for the Honda contract would be to travel to Southern California to visit some of the converters in that part of the world. There were many.

Gage started in the industrial areas around Los Angeles. The towns surrounding LA, once an area of farms and orange groves, were now rife with small industrial firms in prefab metal buildings, some of which were not much bigger than a two-car garage. What he found there disappointed him. Most of the companies were small shops with limited technical knowledge. The converters weren't savvy. They were only doing the basics. They'd rip out a car's guts—the engine, transmission, fuel tank, exhaust system—and replace it with batteries and a DC motor or two. Almost all of the motors were rebuilt; a few had actually come from washing machines. "I was uninspired by the guys doing the conversions," Gage recalled. "They were guys like me, putting wrenches on cars and strapping together a bunch of batteries. The cars were underpowered and their range was short."

The final stop of Gage's uninspiring day was at a small shop in San Dimas, a little town in the San Gabriel Valley, about thirty miles east of Los Angeles. At first it seemed like another disappointing visit. The shop was small, only about three thousand square feet. There were five employees. The company, known as AC Propulsion Inc., didn't even have a conference room. After a few minutes, Gage realized that the building's tiny lobby doubled as its conference room and its office.

The proprietor, however, differed from everyone else Gage had met earlier in the day. Alan Cocconi, founder of the company, was doing things that no one else, *anywhere*, was doing. He was using an AC motor, which he had designed and built himself. He was also using a complex inverter—an electronic device that changed the DC current from the battery to AC for use by the motor. Cocconi had designed that as well. More, he was doing things with battery management that Gage had never heard of previously

In truth, Gage didn't know the half of it yet. Alan Cocconi was the type of engineer normally found in a high-tech government research lab. He wasn't the sort who you'd expect to see in a little garage. A Cal Tech graduate, he had spent his college summers working for GM as a GM Scholar. Later, he'd been the one behind the extraordinary acceleration of GM's EV1. He was not only the designer but the builder of GM's inverter. He'd pieced it together by himself, soldering every one of the inverter's five thousand pieces to various circuit boards. GM had dearly wanted to hire him and had reportedly offered him a big salary. But Cocconi was, to put it mildly, a free spirit. He wasn't about to take a full-time position with GM. He didn't particularly like GM. He did much of his work in his ranch home in the Los Angeles suburb of Glendora, where he just happened to have a lathe, two milling machines, and a bending brake.[3] After leaving the EV1 program, Cocconi had returned to California, then had gone out and bought a shiny new white Honda CRX coupe, torn it down, and installed his own electric powertrain in it. He then showed it to the California Air Resources Board regulators, who declared its performance better than that of GM's Impact.[4] It had an all-electric range of 131 miles and a zero-to-sixty time of eight seconds. The vehicle was so good that he'd been able to sell the drivetrain to Honda for $40,000. Cocconi had then used the money, along with $200,000 of his savings, to start his own company. He called it AC Propulsion Inc.

Gage knew little of this background, but he quickly realized that he was in the presence of someone extraordinary. If there had been a shred of doubt, however, that was soon dispelled. Cocconi handed him the keys to the Honda and invited Gage to drive it. "I drove it around, accelerated it up a ramp and onto the freeway, and looked down at the dashboard and was doing eighty miles per hour," Gage recalled. "It was an eye-popping experience."

When they drove the Honda back to the shop, Cocconi told Gage to flip a switch under the dash and floor it. The switch, Cocconi explained, turned off the traction control. Now the wheels were free to spin with full torque. When Gage flipped the switch and hit the accelerator, the tires spun with all the force of the motor, erupting in billows of smoke. Gage immediately realized how powerful this little car was.

"At that moment, I just felt compelled to start working with Alan," Gage said.

The task of evangelizing the electric car was not an easy one for Alan Cocconi. He forever seemed to be explaining that electric cars need not be underpowered, that they could accelerate as quickly as any gas-powered vehicle, and that their engineering was within reach for any automaker with the desire to electrify.

Thus, the invitation to participate in the Partnership for a New Generation of Vehicles (PNGV) symposium in September 1994 was a major opportunity for Cocconi. The symposium was a place where he could deliver his message to people of importance. The PNGV was a Clinton administration program aimed at helping automakers build an eighty-mile-per-gallon car. Vice President Al Gore was scheduled to preside over a series of such symposiums, which were to be held at the White House Conference Center, across from the White House on Pennsylvania Avenue. The meeting was to be attended by all of the Big Three automakers, as well as representatives from the national labs, oil companies, and universities.

It provided a level of exposure that Cocconi, with his little shop, would probably never get again. It was so important that he decided to buy a suit. Cocconi, who had always prided himself on being noncorporate, didn't own a suit, so friends arranged for him to be fitted for one. When the suit was finished, he threw a few things in the Honda and set out to make the forty-hour cross-country drive from Los Angeles to Washington, DC.

The car he drove to Washington, however, wasn't purely electric. It was a hybrid. Attached to the back of his electric Honda was a small trailer carrying a little motorcycle engine, a generator, a gas tank, and a radiator. It looked a little bit like a pop-up camper. The gasoline fed the engine, which, in turn, spun the generator, which recharged the Honda's batteries. Cocconi called it the Long Ranger. With the Long Ranger charging the Honda's battery pack, he could get eighty miles per gallon of gas, which is exactly what PNGV was looking for. No one at the symposium expected any attendee to actually *have* an eighty-mile-per-gallon car, of course. It was merely a program goal. But here it was.

Still, the symposium did not go well for Cocconi. He met briefly with Gore, and with a few auto executives, but was mostly ignored. "He went to the show and he was basically shunned," Gage said. "It wasn't what Al Gore was looking for. The last thing Gore wanted was some one-car-shop genius with a crazy idea."

When it was over, Cocconi hitched up his Long Ranger trailer and drove to Detroit. As long as he was back East, he wanted to make the best of it. Tom Gage flew to Detroit to join him. Technically, Gage was working on a contract for Cocconi, helping with a few auto industry introductions. He wasn't yet a full-fledged employee. In Detroit they met mid-level executives at Ford and Chrysler. They did not visit GM, however, since Cocconi had butted heads with GM executives during his stay with the Impact program. Later, they drove to Ann Arbor and showed the Honda to editors at *Car & Driver* magazine. Their reception was, for the most part, good. Those who drove the car were impressed. Still, no one offered him a contract to license his powertrain technology. The task of getting the word out was clearly not an easy one.

The final meeting in the Detroit area was with a little one-man shop called Piontek Engineering. The proprietor was a former Ford engineer named Dave Piontek. Cocconi and Piontek had talked on the phone and had agreed to meet to discuss a kit car that Piontek had built. Cocconi was considering purchasing one of Piontek's kit cars. Piontek and Cocconi, as it turned out, were kindred spirits. Piontek had spent twenty years as a Ford design engineer but had been frustrated there by his inability to breathe life into his most important ideas. In his last few years with Ford, he had devoted thirty hours a week to the development of his own performance car, working nights and weekends on the side in his home machine shop. Piontek was one of those rare and gifted engineers who could not only design a car but could build it from the ground up, as well. He had built his first car at the age of twenty, while he was still an engineering student at the University of Michigan. He had also fabricated numerous race cars. His kit car, known as the Sportech, included a chassis and suspension, steering gear, body, wheels, tires, seats, and headlights. He even included a little Suzuki motorcycle engine for power. The Sportech, as it turned out, already had its own cult following, having been publicized in *Car and Driver*, *Road & Track*, *Popular Science*, and about a dozen other publications. The car's racy image had even appeared on numerous calendars.

Cocconi was interested in the Sportech kit car because he hoped to use it as the foundation for his own new electric car. "The car fit their needs, mainly because it was lightweight and it looked pretty good, too," Piontek said many years later. "They told me they were building an electric car from a Honda Civic and nobody cared very much to look at it. They wanted something that was lighter, would handle better, and would make an impression. Something that would look good."

After talking with Piontek, Gage and Cocconi drove back to Los Angeles together in the Honda. This, as it turned out, would be the bonding experience that would lay the foundation for the future of AC Propulsion. On the way, they hit an ice storm in Wyoming, a problem for the hybrid's weak defroster. Gage, who was driving, found himself peering through a four-inch-wide opening in the center of the ice-encrusted windshield, hoping he wasn't about to slide off the road. After a few tense hours, they made it through the storm and began talking about *their* next EV, which would be built around Piontek's kit car. They discussed how and where they would place the lead–acid battery pack that would power the car. Shortly afterward, Gage would join AC Propulsion as a full-time employee.

It was the beginning of a new era for AC Propulsion. About a year later, Cocconi purchased Piontek's kit car and began modifying it for use with an electric powertrain. "Alan being Alan, nothing's ever right unless it's exactly the way he wants it to be," Gage remembered. "So he started hacking up the car and changing everything."

Over the next couple of years, Gage and Cocconi and the rest of the team turned the kit car into a legitimate EV. Gage worked on the structure, battery mounting, and suspension. He brought a sense of standard automotive practice to team members who were not, per se, automotive engineers. Cocconi worked on the battery and inverter. He also changed the frame to make room for the car's batteries and its electric drive system. He then altered the fiberglass body, removing the openings that Piontek had placed for cooling of an internal combustion engine. He even changed the headlights.

While the new car was being developed, AC Propulsion kept itself barely afloat by selling converted Hondas at $80,000 apiece. The company sold about ten of them, while supplementing its income by selling electric drivetrains at $40,000 a pop. Income was scarce; AC Propulsion as a company was earning only about $500,000 per year. It still had only seven employees and, even then, couldn't always pay them. Gage had one year in which he earned just $17,000, relying heavily on his wife's salary to pull the family through. For Cocconi, however, times were even worse. "I've stopped taking paychecks for about a year," Cocconi told the *Los Angeles Business Journal* in 1997. "And there were six months last year where the other partners went without pay."[5]

Still, there was just enough income for Cocconi and Gage to finish their new car in 1999. Called the Tzero, it was a hot yellow two-seat coupe with a bright red dashboard. Its name signified the beginning of time. It contained twenty-four sealed lead–acid batteries from Johnson Controls Inc., which were packed tightly and stacked into the sides of the vehicle. Electrical current from the battery pack powered a 220-horsepower AC induction motor. As attractive and fast as the Tzero was, however, the company's partners knew that it would generate only a handful of sales. "Few will buy the Tzero, though many will want to," the company wrote in its own press release.[6] Indeed, its forecast would turn out to be correct; the company would sell only two, each at $120,000.

Still, the car and the company would develop a small but devoted following. Enthusiasts became aware of its exploits in short drag races. With its zero-to-sixty time of 4.1 seconds, virtually no gasoline-burning vehicle could beat it. An article in *Electric Vehicle Online Today* detailed how the Tzero vanquished a Ferrari 550 Maranello, an exotic sports car with a V12 engine.[7] Gradually, the company's reputation grew. Volkswagen signed a contract to work with AC Propulsion on a few concept cars, including an electrified Golf and a Beetle.

Although the company's income stream was still weak, Cocconi, in typical fashion, began looking for new challenges. A radio-controlled model airplane buff, he had come up with an idea for a small solar-powered plane capable of perpetual flight. The idea was for the plane to use photovoltaic (solar) cells on its wings to collect sunlight. The electrical current from the sunlight would power the plane in the daytime, and the rest would be stored in onboard batteries, enabling it to fly all night, when no sunlight was available. To make it work, though, Cocconi needed lightweight batteries. He decided to use a new chemistry he'd heard about in the model airplane community. The chemistry was called lithium-ion.

Cocconi needed funding, however, so he pitched his idea for a lithium-ion battery to the Electric Power Research Institute, which gave him a $10,000 grant to build some test packs. The packs were small—only eleven cells each—because they were designed to fit in the wings and fuselage of the model plane he was building. But as he assembled the packs, Cocconi's fertile mind turned back to the Tzero. What would happen, he wondered, if he put those lithium-ion cells in the Tzero? He couldn't resist the temptation to try it, and spent the next few months, from March to September of 2003, trying to find out.

Although he didn't know it at the time, it was an idea that would have a historic impact on the electric car, and on the auto industry in general.

For Cocconi personally, it was perfect. It was as if his brain had been wired for a project just like this one. An unprecedented, virtually impossible project. It tugged on all the parts of his brain that made him enjoy proving that he was right, and that everyone else was wrong.

Thus, Cocconi set out to build a car that would be powered by thousands of finger-sized lithium-ion cells. "We had nothing to go by," Gage remembered. "But Alan is imaginative, creative, and obsessive, so he devised a way to package all those cells. All soldered and connected together. It was really a work of art.

Intricate and complex to make, but the whole thing snapped together without a single metal fastener."

In all, there were a hundred modules, each with sixty-eight cells. The modules were mounted in the car's side panels, where the bulky lead–acid cells had previously resided. The entire pack weighed about five hundred pounds less than the lead–acid pack had weighed, yet offered three times as much energy. It worked beautifully. With lithium-ion, the Tzero took off like a jet. Its cost was $220,000.

Word, of course, got around. One afternoon while they were still working on the lithium-ion car, Gage got an email from a neighbor who owned a Toyota RAV4 electric and liked to talk about electric cars. The neighbor said a friend from work was interested in the Tzero. "He asked me about the Tzero—how the car feels, etc., but also availability," the neighbor wrote to Gage. In his email he copied his friend from work as a way of introducing him to Gage.

The friend's name was Martin Eberhard.

No one is really sure who first conjured up the idea of stringing together thousands of little batteries to power an electric car. As early as 1993, Malcolm Currie, former CEO of Hughes Aircraft, had floated the idea in a speech at Cal Tech's Athenaeum Club. Currie, who happened to be a PhD scientist as well as a former CEO, was convinced that General Motors could do a vehicle conversion for as little as $10,000 per car by employing scores of little batteries, and his idea was publicly supported by another brilliant scientist, Paul MacCready of AeroVironment.[8] Still, the idea just kept floating out in the ether for nearly a decade, unrealized.

When Martin Eberhard contacted Tom Gage in the summer of 2003, a decade after Currie's pronouncement, it's not known whether he had heard of Currie, or whether he already had an idea for an electric car using thousands of lithium-ion batteries. In later speeches by Eberhard and his business partner, Marc Tarpenning, it would sound as if the idea had started with them.

Eberhard was, in some ways, like Gage. Born in Berkeley, California, he'd grown up a car nut. He had started driving at thirteen on his uncle's farm in Kansas, and from that point on, was hooked on cars. From an early age he read copies of *Road & Track* and tinkered with vehicles.[9] As he grew into adolescence, he would take his girlfriend to the junkyard with him while he searched for parts to keep his clunkers running.[10] Later, he went on to earn a bachelor's degree in computer science and a master's in electrical engineering from the University of Illinois, widely recognized as one of the best electrical engineering programs in the country. The EE degree made him a natural fit for the Silicon Valley, where he later worked and cofounded two start-up companies. At the first start-up, Network Computing Devices Inc., he served as chief engineer. At the second, NuvoMedia, he and Tarpenning created the world's first electronic reader, called the Rocket eBook. They subsequently sold NuvoMedia in 2000 to Gemstar-TV Guide International Inc. for $187 million.

At that point, Eberhard was just forty years old. And he looked even younger. He was tall and slim with salt-and-pepper hair and a neatly trimmed beard. In photos, he favored sport coats and turtlenecks. But the automotive tinkerer, the kid who rummaged through junkyards looking for car parts, was still down there, deep inside.

His entry into the automotive world came somewhat by accident. Around the time he cashed out at NuvoMedia, Eberhard got divorced. Newly divorced and no longer working a day-to-day job, he began looking for other outlets. First, he considered going to law school to specialize in matters involving electronic media. That desire, however, soon disappeared. Then he found a new direction. "Like any macho American dude, I decided the thing to do was go buy a sports car so I would feel better," he said years later. "But I couldn't bring myself to buy a car that got eighteen miles per gallon in the end. I just couldn't do it."[11]

Thus began Martin Eberhard's journey into the world of alternative fuels. In his search for a sports car power source, he began by doing so-called well-to-wheels analyses of efficiencies of various fuels. "Well-to-wheels" referred to the efficiency of the fuel from the moment it was extracted from the ground to the moment it powered a vehicle. He built a spreadsheet of the energy footprint and carbon footprint of every source, including gasoline, diesel, biodiesel, ethanol, methanol, compressed natural gas, batteries, and many others. He then called Tarpenning, whom he knew and trusted. Tarpenning had started out as a computer scientist at the University of California, Berkeley, but even though he lacked auto industry experience, Eberhard trusted him as an engineer. Together, the two began working on the project. They concluded, unsurprisingly, that a battery electric powertrain would be the most efficient. "It wasn't just better, it was dramatically better," Eberhard said later. "It was so much better that it was stunning to us that nobody else was doing it."[12]

Over time, the lithium-ion battery became the core of the Eberhard–Tarpenning plan. At NuvoMedia, they had learned about lithium-ion technology as it emerged from Japan. Seeing its potential, they had decided to adopt it. They had switched their e-readers from nickel–metal hydride chemistry to lithium-ion. And the results had exceeded their best expectations.

The nagging issue, however, was whether lithium-ion could power a vehicle. "The question we asked ourselves was, could you take that battery system from a piece of handheld electronics and scale it up all the way to the size of a car?" Tarpenning said later. "So we did a bunch of math and a bunch of doodles on napkins and concluded, yes, you could."[13]

So they started with math and doodles. They were two neophytes. They had no prototype. They had no intellectual property since their doodles didn't legally count as IP. And neither of them had automotive experience. Their lack of credentials was breathtaking.

Moreover, there was the history: Many great automotive engineers—Preston Tucker and John DeLorean to name two—had failed miserably in efforts to launch new auto companies. There hadn't been a successful auto start-up in the US since Chrysler in 1925.

Thus when Tom Gage met Martin Eberhard in June 2003, he didn't see Eberhard as a man who was about to change the course of automotive history. Eberhard was new, not only to electric cars but to the automotive world. He didn't fully appreciate the relationship between vehicle performance and battery performance, or the effects of acceleration and temperature. He also had ideas that, in short, weren't going to work. "Martin was extremely interested in electric vehicles but very low on the learning curve," Gage recalled later. "But he was very bright and very curious. And he had money."

Indeed, he had money. Eberhard contributed "on the order of $100,000" to AC Propulsion, essentially buying a stake in the company. At the time it was important for Gage and Cocconi because they were purchasing thousands of batteries. And they were paying a contractor to build the battery enclosures. In essence, the new Tzero was a money pit.

So it was that Martin Eberhard became part of the Tzero team, which included Paul Carosa, Dave Sivertsen, Dave Freund, Gage, and Cocconi. Eberhard's main contribution was to help squeeze the batteries into the car. There were one hundred battery bricks, each containing sixty-eight little finger-sized cells made from John Goodenough's lithium cobalt oxide chemistry. They spent months jamming the bricks into the sides of the car. "It was a huge job," Gage said. "And we learned a lot."

None of them worried about the rather unorthodox idea of using thousands of little cells to propel an automobile. For them, cell balancing wasn't an issue (as it had been for Nissan). They didn't feel they needed big cells. Manufacturing of lithium-ion cells had improved significantly over the previous decade; more than a billion per year were manufactured around the world, and there was little voltage variation between them. At first, Gage and Cocconi tested every cell, expecting to find big variations. But they eventually learned that the testing was unnecessary; maybe only one in a thousand cells was out of spec. "We assumed, maybe naively, but correctly, that the cells made on an assembly line were uniform," Gage said. Thus, they forged ahead with their rather unlikely scheme.

When they took the car to a racetrack, they learned just how good it was. Lithium-ion's lighter weight made the Tzero even faster. In acceleration tests, it was a yellow blur, vanquishing a Corvette and a Porsche 911. In a one-eighth-mile drag race, it beat a Ferrari F355 by eight car lengths. There was little doubt that lithium-ion was a viable solution. The new Tzero was even better than the old.

As the new Tzero progressed, Eberhard began to form a vision for his own new company, and he talked repeatedly about it to Tarpenning, who initially told him that he was "nuts."[14] Eventually, though, Eberhard asked Tarpenning what he thought of the name he had conjured up for the new company. The name, he said, was Tesla Motors. Tarpenning typed the name into his ever-present laptop, and in an apparent change of heart replied, "We now own the domain name." The new company was legally incorporated on July 1, 2003. To make it official, they rented an office with three desks and a couple of phone lines in an old building in Menlo Park. Soon afterward, they added a third employee, Ian Wright, a New Zealand–born computer engineer and amateur racer who lived in their neighborhood.[15]

Still, Eberhard kept at it with AC Propulsion. In September, he joined Gage at an event known as the Michelin Challenge Bibendum. The Challenge Bibendum was an environmental vehicle competition dreamed up by the French tire manufacturer Michelin. The company named the event for its rotund mascot, the Michelin Man, known in France as the Bibendum. In 2003, the challenge was held in Sonoma, California, in the wine country about an hour north of San Francisco. Gage drove the lithium-ion Tzero up to Sonoma himself and met Eberhard there. The event included virtually every type of fueled vehicle, from hybrids and plug-in hybrids to clean diesels, hydrogen fuel cell vehicles, and electric cars, among others. What's more, all the big names were there—Audi, BMW, DaimlerChrysler, General Motors, Ford, Honda, Hyundai, Nissan, Peugeot, Toyota, Volkswagen, Volvo, and others. The event was designed to showcase the most advanced vehicles in the world.

But AC Propulsion, with its seven employees and its shoestring budget, stole the show. In events measuring acceleration, energy efficiency, and emissions, it earned top grades. It also performed well in slalom and braking competitions. "The most electrifying performance vehicle at the Challenge Bibendum was

Lithium-ion battery modules were installed in the side panels of AC Propulsion's Tzero electric car. The vehicle used one hundred modules. Each contained sixty-eight finger-sized cells, for a total of sixty-eight hundred battery cells. (PHOTO COURTESY OF TOM GAGE.)

AC Propulsion's Tzero, a bright-yellow, two-seat roadster equipped with 6,800 lithium-ion batteries, usually found in laptop computers," wrote *Autoweek*.[16] Although the Bibendum did not officially declare a winner, the Tzero had driven off with the highest score of any vehicle at the event.

After the Bibendum event, Gage met with two young entrepreneurs named Sergey Brin and Larry Page, who had launched an Internet company called Google LLC in Menlo Park. Gage showed them the vehicle, let them drive it, explained that it used lithium-ion batteries, and tried to convince them to invest in AC Propulsion. On his way back to the Los Angeles area, Gage also phoned Page to let him know the Tzero had gone more than three hundred miles on a single charge. But the Google founders, despite being wealthy on paper, weren't "liquid." They had no cash to invest.

Still, there was a big upside to the aftermath of the Bibendum. The event had inspired Eberhard. He could now see a path to automotive success. He approached Gage and Cocconi, asking them to build a lithium-ion Tzero for him. Gage and Cocconi, however, declined. The Tzero cost too much, was too much work, and wasn't the ultimate direction they saw for their company.

But Eberhard was undeterred. At some point, he and Tarpenning had decided to take a harder look at the market. They were learning an important lesson. They believed the customer was changing. Examining the data on GM's EV1, they discovered that the lessees were among the richest people in California. The average household income, according to their statistics, was more than $250,000 per year. The zip codes of lessees all seemed to be in the wealthy Bel Air neighborhood of Los Angeles and in equally wealthy Malibu. They also discovered data suggesting that well-to-do Californians were buying Toyota Priuses. Driving through Palo Alto, they noticed numerous driveways with two cars—a Porsche and a Prius. Or an Audi and a Prius. Or a Lexus and a Prius. They learned that Prius sales were, strangely enough, cutting into Lexus sales, despite the fact that the Lexus was a luxury car, whereas Prius was a small entry-level vehicle. Environmentalism, they concluded, had come to the doorstep of the wealthy. "Our take on this—as to why customers buy cars—[was that] it isn't to save money," Tarpenning later said. "It's to project their values."[17]

It was an amazing conclusion. Here were two men, twenty-four hundred miles from the Michigan-based mecca of the auto industry, yet they were savvy enough to identify a gaping hole in the market, even while thousands of auto executives who'd spent their lives in the industry were missing it. For them, the message couldn't have been clearer: Wealthy consumers, especially those in California, no longer wanted gaudy Cadillacs and Lincolns. They wanted environmental salvation. And Detroit wasn't delivering it.

Thus, they concluded that the best strategy for electric cars was to start at the top of the market, rather than the bottom. They studied thirty years of electric car introductions and found a pattern—a succession of pathetic little putt-putt cars, all aimed at the bottom of the market. Detroit, they said, was missing the boat. "The whole previous narrative about electric cars, we thought, was completely wrong," Tarpenning said.

The problem was, Eberhard and Tarpenning had no car. They could hold forth all they wanted about Detroit's myopic view of the world, but they still had nothing. The Tzero was not theirs. It was AC Propulsion's. That was a problem they needed to remedy quickly. "Around November, Martin came to us and said, 'If you're not going to build any more Tzeros, then I'm going to build one for myself,'" Gage recalled.

So it was that two engineers who had never designed a shock absorber decided to build a groundbreaking new alternative fuel car from scratch.

They knew they were in over their heads, so they began their journey by looking for a partner—an auto company that knew how to build cars. They studied virtually every major and minor automaker and concluded that Lotus Cars Ltd. in England would be a good match. Lotus was, in fact, an exceptionally good fit for a fledgling company wanting to build a two-seat sports car. Lotus had vast experience in Formula One racing; it had made powertrains for Chevy Corvettes; it had done a chassis for an Aston Martin; and its racy vehicles had appeared in two James Bond movies. So in November of 2003, Eberhard and Tarpenning went to the Los Angeles Auto Show, where they found famed Lotus automotive engineer Roger Becker. They began pestering him and some other Lotus executives. Worn down by their persistence, Becker and the other Lotus officials led them to a conference room behind the company's booth and listened to the pitch of the two California dreamers. At the end, one of Lotus executives said, "You come to England and we'll talk about it."[18]

A few minutes later, Gage found Eberhard and Tarpenning at the show. They were ecstatic. They felt they had made progress. Lotus was at least listening to them. “They came back from talking to the Lotus guys and said, ‘We passed the Bozo test,’” Gage would later say.

Now there was reason for celebration. They weren’t bozos. But they had a very big chore ahead—funding development of their proposed car. After an encouraging visit with Lotus in England, they set out to find investors. To wow the investors, however, they still needed a car for show-and-tell. The only viable solution was the Tzero. The Tzero had already changed many minds, and its acceleration was something that skeptics had to *feel*.

In the winter of 2003–2004, AC Propulsion lent the Tzero to Eberhard. Eberhard needed it. He needed funding, and it would be almost impossible to convince investors to put money in his company by simply sliding a business plan across a desk.

His idea was to show the car to venture capitalists. In the beginning, Gage joined him. They began by cold-calling—driving up and down Sand Hill Road in the heart of the Silicon Valley, where all the venture capitalists worked, and doing little demonstrations. They let the VCs sit in it, drive it, punch the accelerator. Most of the VCs, however, showed only mild interest. The results should have been disheartening.

But Eberhard was not easily discouraged. In December, he proposed a demo at Buck’s of Woodside, a popular restaurant–tavern in San Mateo County frequented by tech entrepreneurs. At five o’clock in the evening, Buck’s probably had more venture capitalists per square foot than any building in the country. Eberhard’s idea was to “show off what a real electric sports car can do,” he wrote in an email to Buck’s owner, Jamis MacNiven. MacNiven happily obliged. The demo was on.

Once again, Gage joined him. The two of them showed off the Tzero and described its technology to curious entrepreneurs and to venture capitalists in the parking lot outside Buck’s. Each had his own reasons for the demo: Eberhard needed investors to help get Tesla Motors off the ground; Gage needed investors for AC Propulsion’s next big project, a car called the eBox. The eBox was, in truth, a Toyota Scion, a boxy-looking little vehicle aimed at younger buyers. Gage and Cocconi wanted to convert the $20,000 Scion to an electric car and then sell it for $65,000. The goal was to make a practical electric car, one that would be accessible for the middle class. Thus, each man had his own agenda on that day.

The demo at Buck's yielded little, however, with one exception. Gage did manage to get the name of a potential investor from Google cofounders Sergey Brin and Larry Page, who were both there. Brin and Page said they knew of an individual whose funds were "liquid." What's more, this individual liked fast cars. He had just sold his stake in a company called PayPal, and he might be interested, they said.

His name was Elon Musk.

Gage did not yet know Musk, but Musk was familiar with the Tzero's reputation. He'd heard about it from a young Stanford engineering grad named JB Straubel, who liked to hang around at the AC Propulsion shop. Musk, as it turned out, was intrigued by story of the Tzero. He was enamored with fast cars. He had already purchased a million-dollar McLaren F1, one of only sixty-two such cars in the world. He also owned a BMW M5 sports car and a 1967 XK-E Series 1 Jaguar roadster.[19] Moreover, he loved the idea of an *electric* sports car. He had earned a bachelor's degree in physics from the University of Pennsylvania a few years earlier, and in a two-day, temporary stay as a PhD student at Stanford, he had intended to do a thesis on solid-state capacitors for use in electric cars. The thesis had never materialized, but his passion for electric cars had remained. So when Gage emailed him, it was hard to resist. "Sure, I would enjoy seeing it," Musk wrote back. "Don't think it could beat my McLaren (yet) though."

Gage drove the car to Musk's new space exploration company, called SpaceX, in the first week of February 2004. At the time, SpaceX headquarters was located in a warehouse in El Segundo, about twenty miles south of Los Angeles. During his minutes there, Gage went through his sales pitch. There was a void in the market, he said. GM had abandoned the EV1. Toyota, Honda, Ford, and Chrysler were shutting down their electric car programs. California's ZEV mandate had been plundered. EV technology, he said, was getting a bad rap. Yet, here was the Tzero— an electric car that could take off like a jet. The Tzero proved that the technology was readily available. He and Cocconi wanted to use that technology to make an electric car that was useful and practical. They called it the eBox.

Musk, however, wasn't interested in the eBox. He drove the Tzero and decided he wanted *that*. It was a toy he couldn't resist. "I want to buy it," he said. Gage told him it wasn't for sale. Undeterred, Musk offered a quarter million dollars if AC Propulsion would squeeze its lithium-ion battery pack into his Porsche. Gage declined again. AC Propulsion needed money to electrify a Toyota Scion, Gage said. He and Cocconi wanted to build the eBox, and they needed funds to finish the project.

Musk shook his head. The idea seemed incredible to him. "Who wants to take an ugly $20,000 car and buy it for $65,000?" he asked. "I wouldn't want to drive it. My wife certainly wouldn't want to drive it."[20]

It was clear that Musk would never be sold on the eBox idea. Musk liked hot cars, and the eBox wasn't hot. "Well, if you want to do a sports car, then you should talk to Martin Eberhard," Gage replied.

A few weeks later, Gage sent an email to Eberhard, introducing him to Musk. "Elon Musk heads up SpaceX, is a car enthusiast," he wrote. "He would be interested in hearing about your activities at Tesla Motors." Eberhard came back with a quick email of his own: "Any chance of my borrowing the car for next week?"

Eberhard set up a meeting with Musk for April. By this time, Tesla Motors was nine months old and moving forward. It now had three employees—Eberhard, Tarpenning, and Wright. And the founders were putting the technological building blocks in place. They had arranged to pay a licensing fee for AC Propulsion's drivetrain technology, which included the AC motor, inverter, battery management system, and dashboard computers. They were also making arrangements to use a two-seat roadster from Lotus, called the Elise, as their new car's chassis. Still, they estimated that they needed $6.5 million to go further.

In April Eberhard met with Musk. The meeting with Musk, he found, was far different than those he'd had with the venture capitalists on Sand Hill Road. Many of the venture capitalists knew and respected Eberhard and Tarpenning from their success at NuvoMedia. But this . . . an *auto company*? Here were two men who'd never built a car, trying to start a company to compete with the giants in Detroit. Automotive start-ups required deep pockets and tremendous manufacturing proficiency, and these men had neither. All they had was a business plan. It was hard not to be skeptical.

But Musk was different. He wasn't averse to risk—at least not intelligent risk. He was a tech entrepreneur, one who had cofounded a company and then sold it for a whopping $1.5 billion. He loved technology; he loved technical challenges; he loved proving that the impossible *was* possible. "You're presenting an electric car company to this person on the other side of the table, and he's doing something even crazier," Tarpenning recalled later. "He's building rocket ships."[21]

Musk listened, then invested $6.35 million.

Tesla Motors was in business. All it needed now was someone to design and build a groundbreaking electric car.

JB Straubel was young, but he made up for his youth with enthusiasm, brilliance, and a level of persistence that bordered on obsessiveness.

He first met Musk for the same reason as so many other hungry young entrepreneurs: Musk had money. They got together over lunch in the fall of 2003, when Straubel was just twenty-seven years old. He actually came to the meeting as a tag-along with legendary aerospace engineer Harold Rosen. Rosen, seventy-seven, was a giant in the world of technology. He had designed and built the first geosynchronous satellite forty years earlier and was well known for his work in the fields of guided missiles and radar. Over the years, he'd earned more than eighty patents. He had taken on Straubel as a protégé, in part because he recognized the innate talent of the young engineer. On this day, Rosen and Straubel had come to talk to Musk about an idea for an electric airplane.

The electric plane idea died rather quickly, however. Musk had no interest in investing in any such scheme. But in the course of the discussion, Straubel happened to mention his personal passion—electric cars. Over the preceding months, Straubel had been trying to build a battery-powered car with a thousand-mile all-electric range. Straubel was convinced he could do it by stringing together ten thousand little lithium-ion cells. He believed that if the car was light enough, and if the battery made up 80 percent of its weight, it could easily do a thousand miles.

It was, of course, an incredible claim. All of the major automakers of the day were shutting down their electric car programs, and none of them had come remotely close to a 1,000-mile range. Nissan's Altra (which used lithium-ion) had a range of 120 miles; Toyota's RAV4 EV, 118 miles; GM's EV1, a little over 100 miles; Honda's EVPlus, 70 miles; Chrysler's EPIC minivan, 68 miles; Ford's Ranger pickup, 58 miles; and GM's S-10 electric pickup, 45 miles. Yet here was Straubel talking about a 1,000-mile electric car.

But Jeffrey Brian Straubel was, if nothing else, passionate. Known as JB (he insisted on his initials being unpunctuated), he was a dark-haired, clean-shaven, baby-faced engineer who was virtually unstoppable once he began talking about energy. And he'd been that way for roughly half his life. His obsession with electric cars had started as a child in Egg Harbor, a quaint little tourist town in the middle of Wisconsin's Door County peninsula. While walking past the maintenance shed of the town's Alpine Golf Course, Straubel had spied some unused equipment—in essence, a golf cart graveyard. The dead, rusted carts piqued his interest. He promptly announced to his parents that he wanted one of them. "I fell in love with the idea of bringing one of those golf carts back to life, so I started figuring out what made it run so I could refurbish it and get it going again," he said later.[22] He and his parents dragged a golf cart back to their garage, where the fourteen-year-old took the cart's motor apart and rebuilt it. When he needed parts for the brush-type DC motor, or needed batteries, his parents were at his disposal, since he was an only child. Often, the parts were unavailable in the tiny town of Egg Harbor, so his mother would drive him, sometimes as much as fifty miles, in search of six-volt lead–acid batteries, or motor parts, or wiring. Ultimately, he breathed life back into the golf cart and kept it running. It was his first electric car.

But the golf cart turned out to be only the beginning for Straubel. His passion for technology gradually emerged, apparently an outgrowth of his ancestry, going all the way back to his great grandfather, who had started the Straubel Machine Company in the 1890s. Straubel Machine had, somewhat ironically, been a manufacturer of internal combustion engines. By the time Straubel reached high school, he was following in his great grandfather's technical footsteps. He constructed a large chemistry lab in the basement of his family's home. He had a vast array of chemicals and even an industrial fume hood down there.[23]

By 1994, he was accepted at Stanford University as a physics student. But while he did well, the theoretical nature of physics didn't appeal to him, so he switched to engineering, which served his desire to build things. Stanford accommodated its bright young student, allowing him to declare his own major. He called it energy systems engineering. He earned a bachelor's degree, then a master's, graduating in 2000.

Still, his university classes weren't enough. He continued to have a desire to build, to get his hands dirty. Shortly before he graduated, Straubel bought a beat-up 1984 Porsche 944 with the intention of converting it to electric. He ripped out the car's guts—the engine, transmission, muffler, and gas tank. Then he began fabricating parts for it in Stanford's student machine shop. In a sense, it was a more advanced version of his Egg Harbor golf cart. Working from midnight to 4:00 a.m.

while taking daytime classes, he created his own electronic controller and charger, then mated those with two electric motors.[24] Finally, he jammed 840 pounds of lead–acid batteries into the Porsche.

After a year, Straubel finished. He believed it was the world's fastest electric car but still wanted to prove it. What good was it, after all, to have the world's fastest electric car and not be able to prove it? He decided to drive his car to a drag strip, but that presented a problem: Even with its 840 pounds of batteries, the Porsche had a range of only twenty miles. To solve the problem, he created something almost as amazing as the vehicle itself. He bought a junk Volkswagen Beetle for $500, chopped it in two with a shop saw, and then attached the rear half (the driven half) of the Volkswagen to the back of the Porsche with a trailer hitch. Then he rigged a remote throttle, which ran from the VW to the Porsche.[25] In this way, he could remotely control the VW's little engine, and use it to push his Porsche down the road, while he sat up front, steering the entire contraption. It was the ultimate kludgy solution; there must have been a dozen easier ways to deliver the Porsche to the dragstrip. But it was vintage Straubel, a classic do-it-yourself solution. Thus, with the rear half of a butchered VW Beetle, he pushed the Porsche to a drag racing event in San Diego, where it registered a quarter-mile time of 17.28 seconds and he officially became the owner of the world's fastest electric car.[26]

Still, it wasn't enough. In the three years after his graduation, Straubel worked as a propulsion engineer for Harold Rosen's company, Rosen Motors, and then as cofounder of a start-up called Volacom, but the EV obsession still smoldered deep down inside. While AC Propulsion was building the Tzero, Straubel kept showing up there, pestering Gage and Cocconi with questions. Finally, the light bulb clicked on. Sitting with some Stanford friends late one night, he began kicking around the concept of the thousand-mile electric car. As he saw it, the car would essentially be a giant battery on wheels. Ten thousand little lithium-ion cells on a lightweight frame, with a lightweight body. After considerable discussion, he convinced a few of the Stanford friends to join his quest to set a world's range record for electric cars.

He then began looking for corporate sponsors. "I was talking to anyone and everyone to promote the idea that EVs had turned a corner," he said a few years later. "I told them that with new battery technology, it was possible to go much, much farther than anyone thought was possible. I wanted to demonstrate my ideas in a working vehicle and break a few perceptions."[27]

Even for Straubel, however, it wasn't clear what this would lead to. He didn't plan to sell the car, nor convince Detroit to build it, nor start his own company. But that didn't matter, not really, because he was in the grip of obsession. To get the $100,000 he needed for the car, he started walking the aisles of trade shows, where he handed out brochures to anyone who would take one.[28] He then sent emails to prospective angel investors. "I was shameless," he told author Ashlee Vance.[29] But his efforts yielded little.

Until he met Musk at lunch. Here was someone who clearly understood, and who shared his particular brand of madness. By meal's end, Musk had offered $10,000 to help him fund his thousand-mile car.

A few months later, after Musk had met with Eberhard and Tarpenning, all the pieces started to come together. Tesla Motors needed a chief technical officer. Musk called Straubel and urged him to contact Tesla. "Elon had a much bigger vision for the company," Straubel recalled. "It aligned so well with what I was already doing, it was impossible not to get excited." A few days later, Straubel showed up at Tesla's Menlo Park office to talk to Eberhard and Tarpenning.

Impressed by Straubel's knowledge but concerned with his youth, Eberhard called Tom Gage for an evaluation. Gage knew Straubel as the bright young Stanford engineer who'd been hanging around AC Propulsion for more than a year. "We wanted to hire him but couldn't afford him," Gage recalled. "So when Martin called, I said, 'You should hire this guy.'"

A few days later, Eberhard offered Straubel a salary of $95,000 a year to serve as Tesla's first chief technical officer. It was a fraction of what a Big Three chief could make. Moreover, accepting the position would mean that his thousand-mile electric car would never be built. But none of that mattered. Straubel was being offered his dream job, working for a company that was trying to change the world. He quickly accepted.

Now, all the pieces were in place.

No one in the automotive media, or in Detroit, or in any corner of the global industry, believed that Tesla Motors had even a remote chance of being successful. It was hard enough for an established manufacturer to launch a successful new vehicle, let alone start an entire company. And Tesla, of course, was not an established manufacturer. It was a company headed by people from *outside* the industry. In fact, its position as an outsider was one of its strengths. Its founders didn't think like Detroit automakers. But they still had to build cars. Therefore, the odds were against Tesla's founders from the beginning, which, of course, drove them that much harder.

They started with AC Propulsion's technology. It was a natural decision. They had nothing. AC Propulsion was, in essence, Tesla's unofficial research department and the Tzero was its first crude prototype.

In the beginning, the parallels between AC Propulsion and Tesla Motors were striking. AC Propulsion built a two-seat sports car; Tesla was building a two-seat sports car. AC Propulsion had designed its own AC motor and inverter; Tesla was licensing AC Propulsion's AC motor and inverter. AC Propulsion had constructed its own battery pack—one hundred battery blocks, or "bricks," each with 68 cells, for a total of 6,800 lithium-ion cells. Tesla was employing ninety-nine bricks, each with 69 cells, for a total of 6,831 cells. And, like the Tzero, Tesla's new vehicle used John Goodenough's lithium cobalt oxide chemistry.[30]

But even with the Tzero as a model, the task was enormous. Commercial automobiles, of course, aren't built by hand. They're produced on assembly lines at high speed as a means of reducing cost. As far back as 1925, Henry Ford had made one Model T every ten seconds and had chased all but a handful of America's 299 auto manufacturers from the marketplace in the space of a decade, largely by virtue of low cost. Thus, the lesson for Tesla was clear: Even for small-scale production, automated assembly was a must. To build a remotely affordable car, Tesla Motors would have to make every part of its vehicle manufacturable. Every part would have to be redesigned for automated production. The manual assembly techniques employed by Tom Gage and Alan Cocconi would not work.

By January 2005, Tesla had eighteen employees and a development "mule," or test bed vehicle. The mule used AC Propulsion's exact powertrain technology—its AC motor and inverter. And the mule did its job. It proved the car's key performance characteristics—acceleration, range, handling.

But the mule was only the beginning. In the space of the next eighteen months, until the designers were ordered to "put their pencils down," Tesla would tweak virtually every part of the car. One of the biggest issues was safety, especially battery safety. Because Straubel and the engineering team were concerned about lithium-ion's volatile energy, they added a cooling system that pumped a combination of water and glycol through sealed tubes between the battery's bricks. The cooling system was similar in theory to a conventional car's radiator—its liquid-filled tubes drew heat away from the power source. To further enhance safety, the engineers placed eleven microprocessor-based circuit boards around the battery to monitor thermal and voltage sensors, which would broadcast battery data over communication lines (called a CAN bus) to the car's main computers. With this system in place, they could monitor the voltage and temperature of every one of the 6,831 cells.

At the same time, Straubel's team would redesign the inverter so it could be robotically assembled. They would spend months rewriting the motor control software and changing the controller hardware from analog to digital. They swapped AC Propulsion's fiberglass body for a stronger and lighter (and more expensive) carbon fiber body. They modified the Lotus chassis, lowering the sill to make ingress and egress easier.

None of them had anticipated the difficulties of vehicle development. They spent millions of dollars on safety certifications and crash testing. Siemens AG, which made their air bags, expressed liability concerns. Siemens was worried, not only about the vehicle but about Tesla itself. This led to even more expenditures. As costs mounted, Musk brought in new investors, including Larry Page and Sergey Brin of Google, as well as some big Silicon Valley venture capital firms.

By May 2006, Tesla would have 92 employees and its first completed engineering prototype. But the pace of development was frenetic. Tesla was burning through cash, attempting to raise more funds, falling behind schedule, hiring more employees. The number of employees rose to 120 in September 2006, and then to 144 in November. By early 2007, while the engineering team was testing validation prototypes above the Arctic Circle in Sweden, the number of employees rose again, to 230.

In 2007, each week seemed to bring a new crisis. The car, called the Roadster, was late. There were supply chain issues, transmission problems, cost overruns. In short order, the expected cost of the vehicle jumped from $65,000 to $120,000, then to $140,000.[31] Numerous parts—body, motor, battery pack, transmission, power electronics—had to be redesigned and retooled, even though they'd been created only a year earlier. Nerves began to fray. In August, Eberhard was demoted from CEO to president so the company could replace him with an executive who had large-scale manufacturing experience. In November, Musk asked Eberhard to clean out his office and leave. It was an extraordinary moment—the man who had dreamed up the concept and incorporated the company just four years earlier was being pushed out the door. “The only surprise was that the board no longer wanted me as part of the company,” a shocked Eberhard told journalist Todd Woody in December 2007. “There wasn’t any major disagreement going on, not that I know of anyway.”[32]

Shortly after Eberhard’s departure, Tarpenning left. With Ian Wright having departed to launch his own electric car company a couple of years earlier, none of the original three founders were with Tesla anymore.

Somehow, though, the company survived. The keys were Musk and Straubel. Musk was impatient, intimidating, stubborn, and domineering—and his methods worked. He kept the company together. Straubel, who came in knowing virtually nothing about automotive manufacturing, led a young team up an incredibly steep learning curve in just five years. In June 2008, Tesla delivered its first Roadster. By early 2009, deliveries had exceeded a hundred. By February, they were up to two hundred.

The media loved the story. It had every imaginable element of a great yarn—David versus Goliath, Silicon Valley versus Detroit, progressive versus conser-

Tesla Motors CEO and chairman Elon Musk introduced the Tesla Roadster to the media during Press Days of the North American International Auto Show in Detroit on January 13, 2009. (REUTERS/ALAMY STOCK PHOTO.)

vative, youth versus age. It even had appeal for those who didn't care about electric cars. Musk was just thirty-eight and Straubel thirty-three. Yet, here they were, having beaten the mainstream auto industry at its own game. The Roadster had a 244-mile range, "almost three times that of the GM EV1." It featured a zero-to-sixty time of 3.86 seconds, faster than virtually any gas burner. It was also the automotive darling of Hollywood celebrities. George Clooney purchased one. So did Matt Damon. Early owners also included Larry Page and Sergey Brin of Google. Best of all was the fact that mainstream automakers felt threatened. *Detroit* was threatened. "When Tesla announced they were building a car, that kind of tore it for me," noted the cigar-chomping, seventy-seven-year-old GM executive Bob Lutz. "If some little West Coast outfit can do this, we can no longer stand by."[33]

The news was so good, the surrounding optimism so great, it overshadowed the car's obvious challenges. The truth was that its base price of $80,000 (it usually, however, sold for more than $100,000) put it out of reach for probably 98 percent of the population. And with just two seats, its practicality was limited. It also needed three and a half hours to recharge its 990-pound battery pack. Still, its performance reviews were glowing. "You can have enormous fun within the legal speed limit as you whoosh around unsuspecting Camry drivers, zapping from forty to sixty miles an hour in two seconds, while the startled victims eat your electric dust," wrote *Wall Street Journal* editor Joseph B. White in one of the more inspired reviews. "The message is that 'green technology' can appeal to the id, not just the superego."[34]

It was essentially a Ferrari, without the guilt. *Time* magazine named it among its Best Inventions of 2008. Straubel and Musk, as well as Eberhard, Wright, and Tarpenning, became celebrities. They were counterculture heroes. In the eyes of much of the country, they had *invented* the electric car.

The forgotten part of the story, however, was AC Propulsion. In truth, the Tzero had not only been the inspiration for the Tesla Roadster, it had been the prototype. Much of its DNA was still there. Cocconi had developed the motor and inverter; he had designed the battery pack; he had dared to use thousands of little lithium-ion cells; he had shown the world that an electric car could beat a Lamborghini; he had lit the path for Tesla's new marketing scheme. In essence, the modern EV was now being built atop Cocconi's shoulders.

Even Musk would acknowledge AC Propulsion's role. In an online history published in June 2009,[35] he would write that when Eberhard had first approached him in 2003, "he did not have a prototype car and he owned no intellectual property relating to electric cars. All he had was a business plan to commercialize the AC Propulsion Tzero electric car concept." Musk said he personally "tried repeatedly to convince AC Propulsion to commercialize the Tzero, but they were not interested."

Eventually, the relationship between Tesla and AC Propulsion would deteriorate. After the first five hundred cars were built, Tesla would stop paying royalties on the electric powertrain, noting its extensive changes to Cocconi's original concept. Gage and Cocconi would actually buy a Roadster and tear it down, trying to determine whether Tesla's claims were true. But eventually, AC Propulsion would give up on making any legal claims, concluding, as Gage would later say, that "only the lawyers would have gotten rich."

Thus, with each retelling, AC Propulsion would fall farther into the background. Musk would never lie; he would never hide it. But the story of Tesla's rise would grow so amazing, its day-to-day successes and setbacks in the news would be so compelling, that there was little need of any such detail. Eventually, AC Propulsion would become a historical footnote, recognized mostly by enthusiasts.

But in 2009, as Tesla rolled out more shiny new Roadsters, none of that mattered. Although the company was struggling financially, it was laying bigger plans. There would be another vehicle, a sedan code-named White Star. It would use twelve thousand lithium-ion cells. The idea of employing little batteries had succeeded and was, in fact, gaining momentum.

It had been twenty-nine years since John Goodenough's discovery of the lithium cobalt oxide cathode, and eighteen years since Sony's introduction of the lithium-ion battery. And now, lithium-ion was finally making its grand entry into the automotive world. Whether Detroit knew it or not, the new era of the electric vehicle had arrived.

And the auto industry would never be the same.

9

Detroit Awakens

In November 2004, shortly after General Motors had announced it was pulling the plug on the EV1, Mark Verbrugge was called upon to explain the auto industry's growing interest in lithium-ion batteries to a group of GM technical leaders.

The GM leaders had selected Verbrugge for good reason: He knew about lithium-ion, having watched its evolution for thirteen years, and he supported the idea of using it in electrified vehicles. Moreover, he had a command of the subject that gave him an air of authority. Verbrugge had a PhD in chemical engineering from the University of California, Berkeley, and was accustomed to giving talks at technical conferences. He had a knack for boiling complex matters down to their essence. He had also spent his entire eighteen-year professional career with GM and understood the nature of the information that the GM leaders sought.

The leaders present at the meeting represented the top tier of technical people out of the thirty thousand or so scientists and engineers at General Motors. On this particular day, the group of leaders included Larry Burns, GM's vice president of Research and Development; Jim Queen, vice president of GM's North American Engineering; Larry Nitz, executive director of hybrid and electric powertrain activities; and Bob Lutz, who had served as a high-level executive for all of the Big Three automakers.

All of the attendees were concerned about going down another blind alley. They were coming off the EV1 debacle, which had cost GM between a half a billion and a billion dollars (depending on who you wanted to believe). Unlike all of the other automakers, GM had not gone into electrification half-heartedly. It had built the EV1 from the ground up, spending tens of millions of dollars on batteries, motors, inverters, chargers, tires, electronics, and materials for the body and chassis. It had acquired its own battery company—GM Ovonics. And it had changed battery technologies twice in midstream, from a first-generation lead–acid to a second-generation lead–acid, then to a new chemistry called nickel–metal hydride. Ultimately, GM had also joined all the other major automakers in a protracted and painful lawsuit aimed at the California Air Resources Board, which was now, at long last, reaching a conclusion.

Thus, the talk of another emerging battery chemistry brought back bad memories. Besides, claims about battery chemistries almost always seemed to be out of step with reality. The difference between laboratory batteries and production batteries were often great, and the numbers claimed by battery manufacturers were notoriously inaccurate, and sometimes dishonest.

And there was another matter. With the gutting of the CARB mandate came a new era, the era of the hybrid. Many automakers believed that the CARB mandate had been levied before electric car technology had been ready. But the hybrid, which paired an electric powertrain with a gasoline engine, was another matter. Its viability was being proven by the brisk sales of the Toyota Prius. The decade of the hybrid had arrived, they thought.

Mark Verbrugge, however, knew all of this and was still a believer in the potential of lithium-ion. Moreover, his entire professional life was with GM; he knew what GM leaders wanted. Verbrugge had joined GM in 1986, coming straight out of the PhD program at UC Berkeley. He had arrived knowing nothing about electric cars, or GM, or even Detroit. For his first job interview, which occurred in the spring of 1984, he had purchased a wool suit so he'd be prepared for Detroit's cold weather, but he had arrived on a day in the late spring when the temperature had uncharacteristically climbed to ninety degrees. He'd been taken for a ride in an electric car, which broke down, forcing him to hike back to the Technical Center in his dress clothes. "I sweated, not just through my shirt, but through my wool suit," Verbrugge said later. "I always thought they gave me the job out of pity."

Once he started, though, Verbrugge learned quickly about Detroit and the auto industry. He spent a few years working on fuel cells at the GM Tech Center before shifting into battery work. To his surprise, he found that GM was the world's biggest battery manufacturer; its Delco-Remy Division in Indiana produced millions of lead–acid batteries every year.

It didn't take long before he began tracking the emergence of the lithium-ion battery in the early 1990s. He was aware when Sony began producing it in 1991, and he watched as the electronics industry put it into camcorders, laptops, and then cell phones. He was amazed by lithium-ion's energy density numbers. He'd grown accustomed to lead–acid, which had a relatively static energy density of about 40 watt-hours per kilogram. But the energy figures of these new lithium batteries were climbing every year—from 80 watt-hours per kilogram to 120, then to 155. The ascension was like nothing he'd ever seen.

Verbrugge understood lithium-ion not just as a scientist in the lab, but as an engineer as well. In 1994, in an effort to groom him for engineering management, GM had sent Verbrugge to MIT on a Sloan Fellowship to earn an MBA. When he returned, he had succeeded Ken Baker as chief engineer of the EV1. The upshot was that he learned not just about batteries but about electric cars as well.

His deeper immersion into lithium-ion occurred after his EV1 tenure. In the late '90s, GM had begun testing lithium-ion in vehicles. None of the vehicles left the confines of the GM grounds. Engineers drove them only around the roads of the Tech Center in Warren or at the Milford Proving Grounds, about forty miles northwest of Detroit. They employed the chemistry invented by Mike Thackeray and John Goodenough—lithium manganese oxide—and were generally impressed by its performance, if not its cost.

So when Mark Verbrugge came to talk to GM leaders about lithium-ion on this particular day in November 2004, he was prepared. He told them about the tests and the energy density. Lithium-ion, he said, had nearly three times the juice of the lead–acid batteries used in the EV1. And it had 50 percent more than nickel–metal hydride. More, it was succeeding in electronics applications around the world. Every day, consumers of electronics were "testing" it in the field.

Still, Verbrugge hadn't been prepared for the response. There was an inertia in the room, and it was there for good reason. These leaders had lived through two eras of failed electric cars. They'd seen the Electrovair, Electrovette, and the EV1. They'd heard about the promise of silver–zinc, zinc–nickel oxide, advanced lead–acid, and nickel–metal hydride. The executives explained to him that GM had just spent an extraordinary amount of money on GM Ovonics, and had spent another bundle learning how to integrate nickel–metal hydride into vehicles mechanically, thermally, and electronically. Nickel–metal hydride was still *new*, they said, and now they were supposed to throw it all away to dive into lithium-ion?

Verbrugge, however, was adamant. Nickel–metal hydride, he said, had been superseded. There was a newer, better chemistry, and they needed to be ready for its emergence. "There were people in that room who were very upset with me," Verbrugge recalled later. "They were coming unglued because I was saying, 'No, that ship has sailed. We've got to move on to lithium-ion.' It was a hard meeting."

Verbrugge, however, wasn't alone. Bob Lutz listened. Lutz was a veteran of hundreds of boardroom battles. He was a big man with thick white hair, a gravelly voice, and an intimidating air. Lutz thought a minute and then weighed in. The lithium-ion battery needed to be taken seriously, he argued. GM would be making a mistake by overlooking it. The senior technical people in the room were having none of it, but Lutz didn't care. He kept going, and the tension in the room rose. "At one point, he turned and said, 'I'm peeing against the wind, and it feels wonderful,'" Verbrugge recalled.

It was a day, Verbrugge would later say, when he could feel the tide changing ever so slightly. "He was my advocate," Verbrugge said. "He was taking in a lot of the heat in the room because people talk to the most senior person."

Thus, at GM, lithium-ion was in the running, if just barely.

To many, Bob Lutz looked like the epitome of the old-fashioned automotive executive. By 2004 he was seventy-two years old, and his experience in the auto industry stretched back to the days when Detroit was Detroit, and it built big, heavy, powerful gas-guzzling cars. Lutz loved those days because he loved cars. When he'd worked for Chrysler, he'd been the force behind the Dodge Viper, a racy two-seat supercar that came out in 1992. At Ford, he'd been credited with the idea for the company's first four-door SUV, the Explorer. At GM, he spearheaded the creation of a thousand-horsepower, sixteen-cylinder concept car called the Cadillac Sixteen.

Few people outside his closest colleagues knew, however, that Lutz supported the idea of an electric car. To many who admired Lutz, it might have been seen as sacrilege. But Lutz was a man capable of holding many seemingly contradictory positions—a fact that even his friends noted eloquently. "With a martini in one hand and a cigar in the other, he will wax passionate on the blessings of vegetarianism," wrote former Chrysler CEO Bob Eaton.[1] "He's deeply upset that our schools will tolerate students who behave like he once did." Moreover, Lutz often complained about nontechnical leaders with MBA degrees, although he himself was a nontechnical leader with an MBA degree. He had no formal engineering background, whereas many of the scientists and engineers who worked for him had advanced technical degrees. Yet he aligned himself with the engineers. He considered himself a "car guy."

That, however, was Lutz. Bob Lutz was a man who climbed the corporate ladder in all of the Big Three automakers, largely through the immense force of his personality. He was a big man with a thick neck who looked as if, at a younger age, he might have been capable of playing linebacker at the University of Michigan. Born in Zurich, Switzerland, in 1932, Lutz had leadership in his lineage. His father was vice chairman of the Swiss investment bank Credit Suisse Group AG.

His early life was one of privilege. He was unlike his automotive colleagues, many of whom were Midwestern boys who grew up hanging around racetracks and garages. His family, he said, never owned a "dull car."[2] His father drove a 3.5-liter SS Jaguar, and his "rich uncles" variously owned an Italian Alfa Romeo Zagato, a French Talbot-Lago Pourtout, and a 1948 premium French car called a Delahaye. By age eight he had crossed the Atlantic five times, and by eleven he had become a citizen of both Switzerland and the US, as his father moved back and forth between jobs in Zurich and on Wall Street.[3] With all the moving, however, young Lutz fell behind in school and at one point was expelled from a Swiss boarding school for having "academic and disciplinary"[4] problems. He finally graduated from high school at age twenty-two. His saving grace was that he had developed a useful facility with languages, having become fluent in English, German, and French. After high school, he joined the US Marines and later served as a naval aviator before enrolling in a production management curriculum at the University of California, Berkeley. By that time, military discipline had changed him. Lutz ended up earning an MBA from UC Berkeley with highest honors at age twenty-nine in 1962.[5] He subsequently worked as a Marine reserve aviator[6] and a vacuum cleaner salesman to support his growing family, then took a job with General Motors in 1963.

He was popular wherever he worked. Plainspoken and never shy, he was also a favorite of the automotive press. When he took executive positions with BMW and later with Ford of Europe in the 1970s, he overshadowed some of his bosses. Don Petersen, president and later CEO of Ford, had said that when he, Petersen, had occasionally visited Europe, people would come up to him and ask if he worked for Bob Lutz.[7] Because of incidents like that, Lutz's notoriety would sometimes work against him, to the point where he would beg journalists (unsuccessfully) not to mention him in their stories. When he'd been at Ford early in his career, it had reached the point where chairman Henry Ford II had grown weary of seeing Lutz's name in the press. Once, when Lutz had arrived late for a meeting, Ford had said, "Well, here comes our movie star."[8]

Lutz was, however, irrepressible. He bluntly said things that appealed to the average consumer, and made comments that his colleagues probably agreed with but preferred not to say. One of his favorite topics was "car guys." He believed automakers were best run by car guys—men or women who were passionate about cars and had an intuitive feel for the product—rather than MBAs and accountants. "Shoemakers should be run by shoe guys, and software firms by software guys, and supermarkets by supermarket guys," he was fond of saying.

His most surprising viewpoint, however, may have been his take on electric cars. Although Lutz didn't dismiss the importance of the environment, he was skeptical of climate change. He referred to the 2006 film *An Inconvenient Truth* as Al Gore's "fictiomentary."[9] Yet, after the demise of the EV1, he wanted GM to build cars that would be favored by the very people who considered Gore's movie to be gospel.

His view on electric cars seemed to be an extension of his uncanny knack for sensing the pulse of the American market. He had spent the better part of a lifetime understanding consumer needs and preferences, and was the force not only behind the Viper and the Ford Explorer but the Chevy Malibu, Cadillac CTS, Buick Enclave, Chevy Camaro, Buick LaCrosse, Saturn Sky, and many other vehicles.

In 2004 Lutz's knowledge of the consumer came into play again with the electric car. He looked at the popularity of the Toyota Prius and reached the same conclusion that Martin Eberhard and Marc Tarpenning of Tesla had—that a select group of wealthy Americans didn't buy cars to display their wealth, but rather to display their values. He disliked the Prius, describing it as "homely."[10] He also believed that the Prius was a financial loser. But his personal preferences didn't matter to Lutz. He wasn't building cars for Bob Lutz; he was building them for the global consumer. Therefore, he recognized the Prius's impact on Toyota's reputation, not only among green consumers but in the press. And he had a hunch that Toyota would follow the Prius with a battery-powered car, a full electric. He therefore concluded that it was in GM's best interest to roll out its own electric car before Toyota. "Only that way, I argued, could we blunt the relentless reputational rise of Toyota, coupled, of course, with the 'gang who couldn't shoot straight' yoke around our neck," he wrote later.[11]

The "yoke around our neck" was particularly maddening for Lutz. As the auto industry changed, he believed, so did the media. He was deeply resentful of much of the American press coverage, saying that "many media practitioners carry an inherent bias against domestic producers."[12] More, he believed that much of the media had cast GM as "evil" and had installed a halo around Toyota and its Prius. It was a phenomenon that both baffled and angered him, given GM's massive investment in the EV1. But he liked to cite examples of the American press bias, particularly one column written by Thomas Friedman of the *New York Times*. In it, Friedman wrote that "having Toyota take over General Motors—which based its business strategy on building gas-guzzling cars, including the idiot Hummer, scoffing at hybrid technology and fighting Congressional efforts to impose higher mileage standards on U.S. automakers—would not only be in America's economic interest, it would be in America's geopolitical interest."[13]

All of this bolstered Lutz's fierce desire to beat Toyota at its own game. His plan was to build a four-seat electric sedan that would offer a two-hundred-mile driving range. And the technological cornerstone of the plan was the lithium-ion battery. Lithium-ion, he thought, would work for a number of reasons. First, its energy density was at least 50 percent higher than that of nickel–metal hydride, the miracle chemistry last used in the EV1. Second, the price of nickel had shot up by a factor of almost three, making nickel–metal hydride's cost benefits less than they'd once been. Third, Mark Verbrugge and the team at GM's Research Center had been testing lithium-ion since the late 1990s and considered it a strong candidate for an electric car.

Still, GM's Automotive Strategy Board was unconvinced. Lithium-ion was not ready for prime time, board members told Lutz. It had good energy characteristics but poor power capabilities, making it good for laptops but less suitable for automobiles. And then there was the issue of the hydrogen fuel cell—GM had stated that it was pursuing fuel cell technology and it didn't want to publicly reverse course. Finally, there was the memory of the EV1 debacle. "Bob, we lost over one billion bucks on the EV1," noted GM CEO Rick Wagoner. "How much do you propose we lose this time?"[14]

In the end, the factor that kept lithium-ion alive was Tesla Motors. As time passed, Lutz returned to the board with a fistful of press clippings about Tesla. Tesla, he said, was building an electric car with 6,831 little lithium-ion cells, and it was turning zero-to-sixty times of less than four seconds. The stories gave weight to his support of lithium-ion. "How could we, the largest and, arguably, the most technologically capable car company in the world, declare the lithium-ion battery not feasible for motor vehicles when some outfit run by a couple of dot-com billionaires was making it work?" he wrote later.[15]

Ultimately, the Tesla pitch worked. It bought Lutz a little leeway. Working with GM engineer Jon Lauckner, Lutz pulled together a team to explore the idea of an electric vehicle powered by a lithium-ion battery pack. Here, however, Lutz and Lauckner departed from the Tesla approach. Whereas Tesla was appealing to the high end of the market with its $100,000, two-seat roadster, Lutz and Lauckner envisioned more of a mainstream sedan. And lithium-ion was far too expensive for a mainstream sedan. At the time, a lithium-ion pack was assumed to cost about $1,000 per kilowatt-hour, meaning that a big fifty-kilowatt-hour battery would cost about $50,000 . . . by itself. The cost of the rest of the car would be additional. Therefore, the battery would have to be small to keep costs down. And a small battery, in turn, would have to be supported by a small internal combustion engine to provide more driving range. Although the description made it sound suspiciously like a series hybrid, GM engineers claimed it really wasn't one, at least not in principle. GM would call the vehicle an EREV (extended range electric vehicle).

The goal of Lutz and Lauckner was to build a concept vehicle that could be publicly displayed—something that could make a big splash, and keep GM a step ahead of Toyota. With the concept firmly in place, GM engineers could then spend the next three years developing an actual production car.

By 2007, GM was ready to show it off. At the Detroit auto show in early January, the company unveiled the concept, calling it the Chevy Volt. In some ways, the unveiling was eerily reminiscent of Roger Smith's introduction of the GM Impact seventeen years earlier—a big midwinter event, marked by throngs of reporters and cameras. This time, however, it was Lutz taking center stage, attempting to convince the world that GM believed in electrification. "If you lived thirty miles from work and charged your vehicle every night when you came home or during the day at work, you could get 150 miles per gallon," Lutz told press conference attendees.[16]

And like the Impact before it, the Volt became a national media darling. It received twice as much press coverage as any other vehicle at the show. Everyone from the *New York Times* to *Newsweek* covered it, along with all of the major television networks. Following the event, more than 250,000 consumers weighed in on GM's website, GM.com, with 99 percent claiming they would consider buying a Volt.

All that remained was to determine whether that Internet enthusiasm would translate to real-life sales.

In the wake of its sodium–sulfur battery experience, Ford Motor Company did not feel any particular urgency to build an electric car. In the late 1990s, it rolled out an electrified version of the Ford Ranger pickup, but the Ranger EV was not a billion-dollar project like GM's EV1; rather, it was a vehicle conversion with an electric driving range of fifty-eight miles.

But a decade after Ford had pulled the plug on its sodium–sulfur–powered Ecostar, word trickled down to a Ford engineer named Mary Ann Wright that the company was again ready to build a battery-powered vehicle. Wright was a vehicle engineer, not a battery scientist. But she had support from the company's highest levels; William Clay Ford Jr., Ford's chairman and great grandson of Henry Ford, wanted a pure electric car in the company's product portfolio. And as director of sustainable mobility for Ford, Wright's responsibility was to get the project moving.

Having the directive from William Clay Ford was critical. In 2005, many of the engineers at Ford had soured on the electric car. At that point, the California Zero Emissions Vehicle (ZEV) mandate had been gutted, GM's EV1 was being crushed, and the remainder of the industry was abandoning their EV projects. Toyota, with its Prius, was lighting the way. The era of the hybrid had arrived, they believed. Therefore, few engineers wanted to be part of a pure electric car project. "For a long time inside of Ford, this was something that not a lot of people wanted to happen," Wright recalled. "It was expensive. It took a lot of money." But having William Clay Ford behind it changed everything.

Mary Ann Wright had worked for Ford for seventeen years at this point. She had arrived in 1988 but had not started her career as an engineer. She came to Ford with an economics degree from the University of Michigan and an MBA from Wayne State University, and had started as a financial analyst in the Ford Parts and Service Division. She wasn't happy there, however. For as long as Wright remembered, she had wanted to be an engineer. At a young age, her father had steered her away from engineering, thinking that it was it was a profession of mostly men, but her desire had remained. Her time at Ford fueled her engineering dream, however. So she reenrolled at the University of Michigan in 1991 to study engineering. It was a long haul. Michigan's engineering program, like most such curriculums, had rigid expectations about the necessary coursework for an engineering degree. It would not hang its engineering degree on work done in economics, or even in graduate business classes. The requirements were very specific and not easily accomplished, especially for someone with a full-time job. Thus, she spent the next five years taking classes at night and on Saturdays before finally earning her bachelor's and then her master's degree in systems engineering in 1996. Degree in hand, she was then reassigned to a reliability engineering post on the Taurus/Sable program. Gradually, she worked her way up to plant manager on the Taurus/Sable, then to chief engineer for the Lincoln D-car platform, and finally to chief engineer on the world's first hybrid SUV, the Escape Hybrid, which earned the North American Truck of the Year award.

There, Wright learned about the nickel–metal hydride battery. Nickel–metal hydride had burst upon the automotive scene a decade earlier to great expectations. It had boosted the range of the EV1 when it was introduced, and it became the chemistry of choice for Toyota's massively popular Prius. It had also served successfully on Ford's Escape Hybrid. But as chief engineer of the Escape, Wright had also seen another side of nickel–metal hydride—the batteries were big and heavy, they took up valuable cargo space, and they changed the vehicle's driving dynamics and altered its front-to-rear weight balance. They also necessitated the addition of structural reinforcement, which, in turn, added even more mass to the vehicle. All of the issues were solvable, and indeed were resolved admirably on the Escape, but they *were* issues. "We had a great vehicle with the Ford Escape, but we did have to make compromises because of weight and cargo space," Wright said later.

In 2005, therefore, Wright faced a new set of challenges. She understood that nickel–metal hydride's issues were bound to be greater on an all-electric car, where the battery was by necessity much bigger. She knew she needed to find a battery chemistry that was more suited to a full electric car. "I knew we couldn't get there with nickel–metal hydride," Wright said. "We would literally have to have a trailer of batteries being towed behind the vehicle."

So it was that in 2005, Wright walked into the office of a Ford battery research manager named Ted Miller. She pulled out her BlackBerry mobile device, which was small and powered by lithium-ion batteries. "Look, Ted," she said. "Look what's happened in the consumer space. There has to be a better solution than nickel–metal hydride. We're starting to hear about lithium-ion going into everything. Why wouldn't we put that in our vehicles?"

For Miller, the answer was easy. Miller knew lithium-ion well; he'd been familiar with it dating back to 1996, when the United States Advanced Battery Consortium had designated it as a long-range automotive solution. More, he had served on the USABC, and he knew about the work being done by suppliers—LG Chem in South Korea, Varta in Germany, Duracell in the US, and Samsung in Japan. Despite the ongoing work, he said, lithium-ion wasn't where it needed to be. He told Wright that the lithium-ion battery in her BlackBerry had its challenges. It used a lithium cobalt oxide cathode, like the one John Goodenough had invented twenty-five years earlier. And cobalt was expensive. It was difficult to obtain. It didn't have the longevity or thermal stability needed for an automobile. "We just knew that [lithium cobalt oxide] wasn't going to work for automotive," Miller recalled. "There was no way we could be dependent on such a rare and expensive material."

Wright, however, wasn't giving up. She pointed out how much better phones had become after suppliers switched from nickel–metal hydride to lithium-ion, how much more talk time they had. She cited the ubiquity of lithium-ion. *Everyone* in the electronics industry, she said, was moving forward with it.

"She lit the fire," Miller said. "She said, 'Tell me how soon we can get this into a car.' Otherwise, we would have kept giving all the reasons why lithium-ion was going to be a challenge."

Wright's timing, as it turned out, was perfect. All of the major cell producers were ratcheting up their lithium-ion efforts in 2005, as were the national labs and even the raw material producers. Therefore, the company's engineers could assume that lithium-ion batteries would improve. Also, Ford engineers knew that William Clay Ford was squarely behind the effort. This was better than having the

CEO behind their effort. CEOs came and went every four or six years, but William Clay Ford's presence was permanent, and so was his commitment.

That was the way it started for Ford. The company's executives were ready; now it was the job of the engineers to deliver. The first task was to get the cobalt out of the lithium-ion battery. Engineers liked to say that the cobalt-based cathode had a "thermal stability problem," which meant that it could catch fire. But the cost issue was equally disturbing. Studies at the time indicated that lithium-ion batteries cost roughly $1,000 per kilowatt hour, maybe more. That meant that a small battery, like those seen in a hybrid, might run $10,000. A big battery, the kind used by a pure electric car with a long driving range, could be $50,000 or more. Little handheld devices, like Mary Ann Wright's BlackBerry, could get away with using a cobalt-based chemistry because the batteries weighed just a few ounces. Not so for automobiles. A battery for an electric car might weigh a thousand pounds or more. Cost-wise, it was a different ball game.

The cost challenge was accentuated by the fact that Ford and the rest of the automotive mainstream viewed electric cars as small, entry-level products. There was nowhere to hide the cost, as there would be in luxury vehicle. It never occurred to them in 2005 that there might be a group of affluent buyers who would be willing to pay *more* for electrification. So it was that Ford's scientists and engineers would have to find a way to get the cobalt out, or at least minimize cobalt, in order to make lithium-ion financially feasible for entry-level electric cars.

For Ted Miller, the solution lay in an up-and-coming chemistry known as NMC (nickel manganese cobalt), which was a form of lithium-ion (this was the chemistry developed by Mike Thackeray, Jeff Dahn, and others) . NMC *did* have cobalt in it. But its level of cobalt was far below that of lithium cobalt oxide. Whereas a lithium cobalt oxide cathode was virtually 100 percent cobalt by weight, an NMC cathode was no more than one-third cobalt. Moreover, Miller and the Ford battery scientists were working with suppliers in hopes of bringing the cobalt level down to 20 percent.

It was a huge task. To those who supported the idea of an electric car, it would later look as if mainstream automakers were dragging their heels. Tesla had made it look so easy—with a small engineering team and little relevant experience, it had produced an amazing vehicle in a comparatively short time. But one of the keys for Tesla was its identification of a market composed of wealthy consumers who would pay dearly for an electric performance car manufactured in small volumes. Because Tesla was right about the market, it was able to do things that a mainstream automaker would never do. It produced its battery packs using thousands of tiny cells because it had no choice; no major battery supplier would work with Tesla due to its small size and its lack of an established track record. So it used, in essence, a quick and dirty methodology by stringing 6,831 commodity cells together, like so many Christmas tree bulbs. And a small but committed market embraced it.

For better or worse, this was not the methodology of mainstream automakers. Mainstream automakers employed automotive-specific components; they would never use laptop cells. Automakers like Ford were targeting the lower end of the market and were teaming with suppliers to create not only the right chemistry but the best format for the batteries. They wanted big cells that were better suited to an automobile. They wanted to optimize not only the battery's energy density and its raw material cost but its manufacturing cost as well. Only in this way would they be able to reduce their costs to a manageable level and make the electric car competitive for the lower end of the market. But it was a long haul. Battery suppliers had no such product on their shelves. The proposed battery would have to be made from scratch.

Thus in some ways the mainstream automakers' advantage became a curse because it allowed Tesla to roar past them in the court of public opinion. While Ford, GM, and the others worked to find ways to boost energy density, cut material costs, and improve manufacturability, Tesla rolled out an electric car using tiny cells. And the world wondered—if Tesla could do it, then why couldn't Detroit?

Still, mainstream automakers weren't dragging their heels. When Ted Miller had joined Ford in 1995, he had been one of ten battery scientists. By the time Ford started ratcheting up its efforts in 2005, the battery group had grown to fifty people. And during the decade after that, the group would grow to include approximately five hundred scientists.

By 2007 it became apparent that Ford and its suppliers were making inroads with the NMC chemistry. It was clear that large-format cells would be available, and they would be manufacturable. Therefore, Ford began to lay plans for two new plug-in hybrids and a fully electric car, the Focus EV. Those vehicles would roll out in 2012. And they would use lithium-ion.

Ford engineers, of course, were unsure if this move to lithium-ion chemistry was a big step forward or another dead end. Its history with EVs was not encouraging—it went all the way back to Thomas Edison's nickel–iron battery in 1914. Edison's battery had been a failure. Then Ford had spent thirty years on the sodium–sulfur battery, only to have it end in flames. Given the historical record, confidence was understandably low.

But with William Clay Ford behind it, the move to lithium-ion had begun. Ford's battery effort was gaining momentum. The number of battery scientists was growing, the chemistry was evolving, the suppliers were investing more money in the technology.

"It took a combination of ingredients," Miller said later. "And Mary Ann Wright just happened to hit it at the right time."

It was the era of the hybrid, but not at Nissan. Carlos Ghosn, the company's CEO and chairman, was not a believer. He saw hybrids as a half measure, a niche technology with a limited future. He publicly referred to them as a "terrible business prospect."[17] Even when his own company rolled out its Altima Hybrid, he expressed doubts about the level of consumer demand for the car.[18]

Ghosn openly expressed his pessimism, despite a prevailing feeling to the contrary, not only in the rest of the auto industry but in the media. In 2005, some saw the hybrid not just as a bridge to electrification but as an end unto itself. Many in the media openly adored Toyota for its success with the Prius, and virtually every mainstream manufacturer was following in Toyota's footsteps and planning its own hybridized vehicle.

Still, Ghosn was unconvinced. Ultimately, he believed the electric car would take over. Ghosn wanted to leapfrog the interim step of making a hybrid and go straight to a full electric car. He compared the hybrid to a person who wants to quit smoking cigarettes, but can't. "If you smoke a pack of cigarettes and your friend smokes only half a pack and I don't smoke, there's a big difference between us," he said. "Your friend with half a pack is an optimized version, but I'm the breakthrough."[19]

Ghosn's belief in the electric car was largely based on Nissan's prior experience with lithium-ion batteries, which had begun before he'd arrived there. Nissan had built and marketed the all-electric Altra in 1998 after an extended period of joint research with Sony Corporation on the lithium-ion battery. Nissan and Sony had built big “jelly roll” batteries using John Goodenough’s lithium cobalt oxide cathodes. Then they’d studied the way drivers had used their electric cars and had concluded that there was a market for the EV.

And then Ghosn had arrived. At first, no one was sure what to expect. Nissan engineers didn’t know which projects would survive Ghosn’s leadership and which wouldn’t. He had come to Nissan in 1999 after Renault S.A. had purchased a 36 percent stake in the company. He’d been the leader at Renault and was immediately appointed the chief operating officer of the new Renault–Nissan alliance. At the time of the merger, Nissan’s financial situation was dire, and Ghosn had arrived with a reputation as a corporate reformer. In France, when he’d led Renault, he’d been known as “Le Cost Killer.” He wasn’t there to maintain the status quo.

Carlos Ghosn was just forty-five years old when he’d arrived at Nissan. A short man with jet-black hair and thick dark eyebrows, he was a citizen of the world. Born in Porto Velho, Brazil, in 1954, he had moved with his family to Rio de Janeiro and later to Beirut, Lebanon, in his youth. In Lebanon, he’d attended a Catholic Jesuit high school before moving to Paris. There, he’d been admitted to the highly selective French grandes école educational system, graduating as an engineer from the École Polytechnique in 1974 and then earning a degree from the French engineering school École des Mines de Paris (Paris School of Mines) in 1978.

From the beginning of his career, he’d been marked for the fast track. At age thirty in 1984, he was named head of research and development for Michelin’s industrial tire division. At age thirty-five, he was appointed chief operating officer of Michelin North America and moved to Greenville, North Carolina. Moving from country to country was not a challenge for Ghosn. He was fluent in French, Portuguese, Spanish, Italian, and English. He saw his transfers not as challenges but as advantages. “The reality of the world is, you learn from diversity, but you’re comforted by commonality,” he said.[20]

By the time Renault acquired its share of Nissan, Ghosn had earned a reputation as “Mr. Fix-It.” He had been widely credited with rescuing Renault from near bankruptcy in the late 1990s, and upon arriving in Japan he’d been expected to do the same. From the beginning, his plan for success was viewed as a radical one in a country where compromise was seen as a way of life. He quickly slashed the workforce by twenty-one thousand, tore down a sprawling but inefficient supplier network, closed three auto plants, shortened the chains of command, shrank Japanese production capacity by 30 percent, globalized purchasing, ended

Nissan's lifetime employment system, and shifted the company's emphasis from production to profitability. One of his first declarations to stunned Nissan executives was, "One rule: no sacred cows; no taboos; no constraints."[21] To Nissan employees, his approach seemed brash, almost disrespectful, but the results were difficult to dispute. By the end of 2000, the company was inching back to profitability. Its $13.2 billion debt had been cut in half, even while Ghosn was boosting its investment in research and development. Moreover, he saved Nissan's commitment to electrification.

And he was recognized for it. For engineering the turnaround, he became a worldwide business celebrity. In 2004, he was named the world's third most-respected business leader in a *Financial Times*/PricewaterhouseCoopers survey, behind only Bill Gates of Microsoft and Jack Welch of General Electric. More, *Fortune* named him Asia's Businessman of the Year. He was even cast a superhero in Japanese comic books.

And he was greatly compensated. He made frequent trips back and forth from France to Japan in a Nissan-owned Gulfstream G650 jet that slept ten and cost more than $67 million. He had luxury apartments in Tokyo and Amsterdam, as well as a mansion in Beirut.[22]

All of this made his commitment to the electric car more surprising. Ghosn was at the pinnacle of his career; there was little reason for him to take risks. Moreover, in 2005, most mainstream automotive executives saw the EV as a money pit. The cost was tremendous and the payback uncertain. The feeling among many was that the people who bought electric cars were a sliver of the market; most probably had too much disposable income. There was not enough of them, they thought, to raise the production volume and change the economies of scale. The magic number in the auto industry was 250,000 vehicles—that was where the economies of scale really kicked in. And industry executives did not believe it was possible for *every* mainstream automaker to reach even a fraction of those sales with an electric car. "Who are the 100,000 soldiers who will sacrifice themselves to drive EV prices down?" one engineer asked the mechanical engineering magazine *Design News*. "Willing consumers aren't out there."[23] For Ghosn—*Le Cost Killer*—to take the opposing side of that argument was shocking.

Still, Ghosn believed that a willing consumer base existed, especially if automakers could improve the battery. And Nissan had spent a great deal of effort on the battery, within its own ranks and with its suppliers. The big cylindrical cells it had used on the Altra were gone, replaced by prismatic (rectangular) cells that could be stacked like wafers. With more efficient stacking, the battery pack would consume less of the vehicle's cargo space. More important, the lithium cobalt oxide chemistry had been abandoned. John Goodenough's chemistry had initially looked good—its energy was high. But Nissan engineers had found it was prone to overheating and was far too costly; the Altra battery was running more than $100,000 per car. So they had changed the chemistry to lithium manganese oxide (invented by Goodenough and Thackeray). Lithium manganese oxide was less prone to overheating, and its cost was far lower. The disadvantage was energy density. Whereas lithium cobalt oxide offered more than 180 watt-hours per kilogram, lithium manganese oxide offered less than 140. The energy penalty would ultimately translate to less range.

In the next few years, Nissan made the decision to go to market with an electric car. It pulled together big teams of engineers at its Advanced Technology Center in Atsugi, Japan, as well as its Research Center in Oppama and its Operations Center in Zama. It was the largest-scale effort Nissan had ever managed, outside of engine design. Other than a few minor parts, everything in the car, including the AC drive motors and inverter, was designed in-house. Using the stackable cell concept, Nissan engineers created a 480-pound battery pack that was shaped to lie flat under the car's floor. When they finished the design, they shipped the battery off to NEC Corporation for manufacturing.

By May 2008 Ghosn told a select few reporters that Nissan was building an electric car. To some it came as a shock. Given his aversion to hybrids, they had assumed he was anti-electric. "Obviously, something has opened his eyes," an industry analyst told the *New York Times*.[24] To those who knew him, however, there was nothing new in his support of electrics. His disdain had been reserved exclusively for hybrids. As if to clarify his position, he later told the *Times*, "I want a pure electric car. I don't want a range extender. I don't want another hybrid."[25]

At the Los Angeles Auto Show in November 2008, Nissan introduced its new EV to the world. Now it had a name—the Leaf. Ghosn, on hand for the press conference, made it clear that Nissan was courting a younger, more enlightened, more environmentally conscious consumer. From an environmental perspective, he said, this car was necessary. "In China, there are fifty cars for every thousand people; in the U.S. there are 800 cars for every thousand people," he told reporters. "We will need another planet if China ever catches up to the U.S."[26]

The media heard the message. The Leaf was crowned Car of the Year in Europe and in Japan. It also received the World Car of the Year Award from international journalists. *Automotive News* called the Leaf "the real deal,"[27] *Motor Trend* declared that "the electric future is here,"[28] the *Toronto Globe & Mail* declared it a "game changer,"[29] *Motor Age* wrote that "tomorrow is here today,"[30] and *Automobile Magazine* said that the Leaf was "a chance to thumb your nose at Big Oil."[31] *Ward's Auto World* also named Leaf's electric powertrain to its Ten Best Engines list by adding a whole new category for electric propulsion.[32] The publication even described its debut as "a monumental event."[33]

It was an amazing collection of accolades for a car with just seventy-three miles of electric range. The Leaf's range was less than that of the GM EV1, the Toyota RAV4 EV, *and* Nissan's own Altra, all of which had hit the market a decade earlier. But the media and much of the public had been primed for a genuine entry into the field of electric cars. And the Leaf was genuine. Nissan was committed to it. The company gave every indication that it would stick with the Leaf, even if there were lean years ahead. As Nissan viewed it, there was more at stake than the success of one model.

Thus, when Ghosn declared that the Leaf would be quickly profitable, the auto industry listened. He believed that it would be worth the billions that Nissan had invested in it, and not for public relations reasons. This, he said, was a real competitor, not a so-called loss leader.[34] He predicted it would snag Prius owners; more than 130,000 of the people who had already expressed interest in it currently owned a Prius, he said.[35] Moreover, the EV market would grow at an extraordinary pace, he said, reaching sales of more than six million units a year by 2020. For that reason, Nissan planned to build fifty thousand Leafs in its inaugural year of production, quickly ramping up to two hundred thousand. By the end of 2013, he told the *New York Times*,[36] Nissan would sell a half million Leafs a year.

To some, the numbers sounded incredible. Yet other automakers were now following. BMW, BYD, Daimler, Ford, Mitsubishi, and Tesla had announced intent to build pure electric vehicles. The EV was making a comeback. The corpse was breathing again.

Moreover, this was Carlos Ghosn—Le Cost Killer, Mr. Fix-It. He was one of the most respected corporate leaders in the world, a man whom *Newsweek* had referred to as a "rock star."[37] He was not one to spend billions of dollars to make a political statement. He was approaching this from a profitability standpoint, first and foremost.

And the world wanted to believe.

The early expectations had been too high. Some observers took it for granted that the electric car would be successful because automakers now wanted it to be successful. There was a sense around the auto industry that a change was afoot, that automakers were on the verge of something big. The media coverage had certainly helped feed this feeling. Automotive writers, always on the lookout for a trend, thought they saw the beginnings of one in the success of the Toyota Prius. Then the Volt and the Leaf had arrived. It had the feel of a historic transition.

By 2013, however, the transition looked less historic. Sales figures of electric cars were a tiny fraction of what had been promised. Nissan sold just 22,094 Leafs worldwide in 2011, and 26,973 in 2012. The figure would rise to more than 47,000 in 2013, but that was still just a sliver of the half million electric cars that Carlos Ghosn had promised for that year alone. GM's Volt was doing no better—Chevrolet sold just 23,094 of them in 2013.

In March of 2013, sensing that the forecasts were not materializing, the press had peppered Ghosn with questions at the New York Auto Show. Ghosn, in his usual way, made a spirited and impressive defense. Yes, the company had spent approximately $5.1 billion developing the Leaf, he said, but that was because this was such a radical and unprecedented transition. The Leaf had cost twice as much to design and engineer as a regular car, he said, and Nissan would one day reap the benefits of that investment. He insisted that the Leaf would still account for 10 percent of Nissan's global sales by 2020 and argued that electric cars in general would also be 10 percent of the market by that year. More, he assured reporters that the Leaf's slow start would not hurt the company. "It's a big stake, but not a stake that will shake the foundations of Nissan," he said.[38]

Ghosn, of course, was not alone. Everyone, including the analyst community, had been fooled. In 2008, Deutsche Bank AG had projected that electric cars and plug-in hybrids would represent 2 percent of the U.S. market by 2012, rising linearly to nearly 7 percent in 2016 and 11 percent by 2020. Other analysts followed with similarly optimistic forecasts. Frost & Sullivan, PricewaterhouseCoopers, and BloombergNEF predicted that EVs would account for approximately 6 percent of the market by 2016.[39] Even the pessimists were projecting a 3 percent penetration. None of the major research firms projected a 0.6 percent penetration in 2013 or a 0.7 percent figure in '15. But that, as it turned out, was the reality.

There were many reasons for the electric car's weak market acceptance. But in the end, they mostly boiled down to the battery. Batteries were far more complex and difficult to develop than the auto industry had anticipated. In a sense, the industry's struggles served as a testament to the work done by Stan Whittingham, John Goodenough, Akira Yoshino, Mike Thackeray, Michel Armand, and hundreds of other scientists over the previous forty years. Battery development had *always* been painstaking and tedious work. The success of the early battery scientists had come slowly, built atop the small insights that fellow scientists had shared in labs, conferences, and scientific papers. There were never any guarantees that those successes could be accelerated simply because they were needed at some moment in history. It wasn't that easy. Donald Sadoway, a noted MIT professor and materials scientist, had described the battery challenge perfectly in 1998, saying: "It's the scientific equivalent of quicksand, deceptively simple, yet enormously complex."[40]

The world, however, did not see it this way. Spoiled by the extraordinary pace of innovation in the semiconductor industry, many executives and analysts had come to believe that *all* new technology advanced in great leaps. They looked at laptops, mobile phones, and flat-screen TVs and assumed the EV was next in line for a market explosion. Thomas Friedman of the *New York Times* even wrote in an op-ed that there was a "Moore's Law of electric cars."[41] GM's North American president, Mark Reuss, had penned a letter to skeptical editors at the *Wall Street Journal*, comparing electric cars to phones. "Remember when mobile phones fit in a brief case, weighed forty pounds and were affordable only to the wealthy?" he wrote. "Now, cell phones fit in your hand, have desktop-like computing power and sell by the thousands every day."[42]

The world, it seemed, had been swept up in the idea that all new technology could be willed quickly into existence and would obediently follow an innovation curve called Moore's Law. Appreciation for the complexity of batteries had been lost in the process. The problem was that Moore's Law described the reduction of feature sizes on semiconductor chips. It did not apply to batteries, engines, tires, refrigerators, air conditioners, washing machines, or virtually any other nonelectronic product. Bill Gates had tried to explain this in a 2010 speech about challenges facing the battery field. "They haven't improved hardly at all," Gates said of batteries. "There are deep physical limits. I am funding five battery start-ups and there are probably fifty out there. [But] that is a very tough problem. It may not be solvable in any sort of economic way."[43] But Gates's warning fell mostly on deaf ears. Expectations forged ahead. The relentless optimism was a product of a phenomenon that energy historian Vaclav Smil called "Moore's Curse."[44]

Believing in a quick transition was, of course, important for the auto industry. Without it, automakers would have to assume that battery improvement might be a long slog. And no one wanted to believe that. The truth, however, was that batteries already faced an uphill battle in three key areas: energy density, recharge time, and cost. As dirty and inefficient as gasoline was, it was still better than batteries in all three of those areas. Whereas a good automotive battery might have an energy density of two hundred watt-hours per kilogram, gasoline offered about four thousand watt-hours per kilogram (the number was actually twelve thousand, but two-thirds was lost as waste heat due to the inefficiency of the internal combustion engine). So, in essence, gasoline offered at least twenty times as much energy as the best batteries while allowing for much faster refueling and providing a big cost benefit on the initial price of the car. Of those, automakers felt that the biggest impediment was initial cost. Lithium-ion batteries were still exorbitantly expensive in 2013. The battery in Tesla's Model S sedan was said to cost more than $40,000, and many Model S buyers were paying more than $100,000 for the car. Given the fact that the average American family was earning $62,272 (according to the 2010 US Census), automakers *needed* to believe that battery costs were dropping fast.

Thus, Ghosn and much of the auto industry clung to the belief that a big battery improvement was imminent. Without it, and in the absence of government incentives, it would be virtually impossible for any company's electric car to turn big sales numbers. Moreover, other manufacturers were coming. Mitsubishi rolled out its electric i-MiEV in 2009, Ford introduced the Focus EV in 2011, Tesla debuted its Model S in 2012, and BMW's i3 made its inaugural appearance in 2013. For all of them, fast battery development was critical.

Still, batteries would not improve as fast as the industry hoped. And EV sales would continue to disappoint. It would take ten years for the Leaf to reach a *cumulative* sales figure of a half million cars, let alone the half million a year Ghosn had projected. And sales across the rest of the industry were no better. In 2018, GM would discontinue production of the Chevy Volt. Indeed, EVs did not come close to the projected penetration of 10 percent by 2020. At the end of 2019, plug-in vehicles (which included plug-in hybrids) accounted for just 1.9 percent of US total sales, and pure electric cars were just 1 percent.

Nissan, however, stuck it out. So, too, did most of the auto industry. For the first time in history, mainstream automakers were demonstrating a commitment to electric cars, despite weak sales and huge ongoing investments.

It was as if they were all heeding the advice that Carlos Ghosn had counseled at the 2013 New York Auto Show.

"We just have to be extremely patient and resilient," he had said.[45]

Beginning in 2015 there were glimmers of change. In January, General Motors announced its intention to build a battery-powered car called the Bolt. It was to be another major electrification effort from GM. "Chevrolet is once again raising the bar by bringing an affordable, long-range electric vehicle to the market," Mary Barra, the company's new CEO, said during a glitzy press gathering at the Detroit Auto Show. "This is a game-changer."

There was, of course, some media cynicism. The reporters who'd been around long enough could remember similar auto show unveilings for the GM Impact in 1990, the EV1 in '96, and the Volt in 2007. They'd finally grown skeptical.

But the cynicism diminished a bit in October 2015 when Mark Reuss of GM made a comment that quickly reverberated across the industry. Reuss had been addressing financial analysts at GM's Global Business Conference in Michigan when he said, almost as an aside, that GM and its battery partner, LG Chem Power Inc., had pared battery cell costs to $145 per kilowatt-hour. Then he added that GM planned to bring that figure down to $100 per kilowatt-hour by 2021.

For those who knew batteries, as most of the analysts did, it was a shocking moment. The numbers were so good, they were almost unbelievable. The auto industry had been working for more than two decades to drive down cell costs, with an ultimate goal of $100 per kilowatt-hour. One hundred dollars, engineers said, was the price at which an electric powertrain reached parity with a gasoline engine. It was the Holy Grail of battery cost. And here was GM, claiming that it would reach $100 in six years. More, it was saying that it, along with LG Chem, was at $145 *right now*. By itself, that was extraordinary. Only six years earlier, the National Academy of Engineering had estimated average lithium-ion cost at more than $1,000. And in April of 2015, just six months before Reuss's comment, the scientific journal *Nature Climate Change* had pegged the going number at $300 per kilowatt-hour.[46] At the time, the *Nature* article had been considered a revelation. Few analysts had imagined that the figure was down to $300. Now, here was Reuss saying that GM's number was less than half of the *Nature* figure.

"It sent a shock wave through the whole industry because now you're talking about a car that everyone can afford," recalled Mark Verbrugge of GM.

Even for some of the electric car skeptics on Wall Street, this was important. Automakers, they knew, could always do a glitzy rollout of a concept car at an auto show, stir up a lot of media coverage, and then change their minds. But this was different. With these new cell costs, a big sixty kilowatt-hour battery pack might cost $8,700 (plus an additional few thousand dollars for the cooling system and electronics). In 2010, a pack of similar size might have cost more than $30,000. And in 2005, it might have cost $60,000. *This* was what the United States Advanced Battery Consortium and the Department of Energy's Vehicle Technologies Office had been targeting for more than two decades.

The key was commitment. And GM seemed to have that covered as well. In 2014, it had appointed Barra as its new CEO, and Barra had made it clear that she was convinced GM needed to grow in new and different ways. She thought it needed to break from the past. And electrification was one of those ways.

By the time Barra had started as CEO, she was, in a sense, a GM lifer. She had grown up in Waterford Township, Michigan, a middle-class suburb about seven miles from the Pontiac Motor Plant, where her father had worked as a journeyman diemaker. From a young age, GM had always been a part of her home. "My whole life, I can't remember my father ever not being at work," she told biographer Laura Colby.[47] "He worked a lot of overtime. The company was always crunching out new models and the dies were changing each time you did that." A high achiever in high school, she'd gone on to college about thirty miles north of Waterford Township at General Motors Institute in Flint, Michigan (it would later change its name to Kettering University). Flint was a GM town and GMI was its mecca of higher education. The school had at one time been known as the "West Point of the automotive industry." It was notable for its approach to education, for combining theory with practice. In addition to conventional math, science, and engineering, freshmen took classes in production processes. To graduate, students were required to serve five co-op terms, which essentially meant working in local GM manufacturing plants. There were plenty of opportunities for positions, given the fact that Flint was home to what later became known as "Buick City," a 235-acre complex of GM manufacturing facilities.

At GMI, Barra studied electrical engineering. In parallel, she began her GM career as an eighteen-year-old inspecting fender panels in a Pontiac factory. It was a no-nonsense education in a no-nonsense city. Students studied and worked. There were no spring breaks or long summer holidays.[48] Co-op service started in the summer immediately after high school graduation. Nor was Flint a "college town" in the usual sense. There was little to do. The kids could go for Mexican food at the local Chi-Chi's, get an ice cream cone at the Howard Johnson's, or, if they were old enough, get a beer at one of the taverns near the factory plants.[49]

Their education, however, served them well. Eighty-five percent of the students were Michigan kids, many of whom grew up surrounded by cars and dreamed of taking their place in the auto industry. Some were children of Detroit auto executives. Some, like Mary Makela (Barra's maiden name), were bright children of middle-class parents who did not have college degrees. Either way, they were there to work. And their education usually rewarded them with good engineering jobs at GM, Chrysler, Ford, or at any of the dozens of supplier companies.

After graduation in 1985, Barra started her career as a controls engineer at a plant that built the Pontiac Fiero sports car. When GM closed the plant, Barra enrolled in Stanford University's MBA program on a General Motors fellowship, returning to GM two years later. After that, her rise through the company was steady. She held a variety of engineering positions, including her management of GM's Hamtramck assembly plant. As she progressed, it became clear that Barra viewed herself as a plainspoken agent of change. When she served as GM's head of human resources, she condensed a ten-page dress code down to two words: "Dress appropriately."[50] When she was later appointed product chief, she immediately had all key cards between her office and the other engineering offices removed, viewing them as symbolic of how GM executives tended to work in siloes.[51]

Her tenure as CEO began with more change. This time it was more dramatic. She considered the company too big, too unfocused. Therefore, she decided to reduce GM's global footprint, exiting Europe, Russia, and India. Whereas once GM had made cars and parts in twenty-five countries, she cut it to just nine. At the same time, she invested in electric cars, believing that they were the future.

The next chapter in GM's EV history began in 2015 with the Bolt. In her comments at the Detroit auto show, Barra implied that the Bolt would not suffer the same ignominious fate as GM's early EVs. "This is no stripped-down science experiment," she declared. "It's an all-electric vehicle for the real world."[52]

The unspoken part of GM's message was that it was targeting Tesla. Inside GM, Tesla had become an irritant. It was not so much that GM was annoyed with the Silicon Valley automaker, as much as it was annoyed with itself. Secretly, many GM engineers professed admiration for what Tesla had accomplished. But there was a sense of frustration, too. GM had allowed Tesla to step in and take the leadership position in the electric car market, largely because many GM engineers had believed that a pure, battery-powered electric car could not be competitive. But Tesla had, to some degree, proved otherwise. As Elon Musk liked to say, "Tesla was cutting a path through the jungle to show what can be done with electric cars."[53] At the same time, though, Tesla was not profitable. From the beginning of 2009 through the end of 2012, it lost money in sixteen straight quarters. More, it was deriving a portion of its revenue through a California Air Resources Board system that called for automakers who didn't build electric cars to buy credits from those who did build EVs.[54] Thus, GM and others were actually *paying* Tesla to build Teslas. It was a situation—an embarrassment—that mainstream automakers were loath to discuss. GM was doling out cash for electric cars that it wasn't even building. For GM executives, the worst part was that it made Tesla look like a winner in the eyes of the public, while GM looked clueless.

So it was that Barra announced the Bolt. The copper-colored vehicle that GM rolled across the stage at the Detroit auto show in January 2015 looked impressive—two hundred miles of electric range for a $30,000 price tag (after the buyer received a federal rebate). And it was clearly targeted at Tesla, which had recently announced its intention to build a "low-cost" electric car called the Model 3. But by this time, of course, GM had a long history of similar announcements (the Electrovair, Electrovette, EV1, and Volt). The media dutifully wrote about it once again. But unlike the earlier years, when GM dominated the news with its electric car fanfare, its car was no longer a lone competitor. Tesla's Model S was slowly building its sales numbers, as was Nissan's Leaf. Moreover, Tesla's media presence had grown greater than that of GM. Thus, the Bolt was less of a story than it might have been in an earlier era.

This time, however, GM felt that the game had changed. Its engineers knew something that competitors did not know—that its battery cost was now down to $145 per kilowatt-hour. Within GM, there was confidence associated with this. At GM's Tech Center in Warren, engineers could now make a more accurate projection of the future costs of a battery. Internally, they were targeting a figure of $100 per kilowatt-hour. They also built up their research and development efforts so that they could *own* the intellectual property of their batteries. They saw LG Chem as the manufacturer but viewed themselves as the boss, even in matters of battery chemistry.

There were many reasons for their confidence. The first and most important of those was the cathode material. John Goodenough's lithium cobalt oxide (a material derisively referred to by automotive engineers as "un-affordium") had always been too expensive for the auto industry. Thus, by 2015, virtually everyone in the auto industry had found an alternative. The most popular of those was NMC (nickel manganese cobalt, invented by Thackeray and Dahn). NMC had been the cathode of choice for GM's Volt and for the second generation of the Nissan Leaf. But even then the cost had been too high. There was still too much cobalt in it, so battery scientists kept whittling down the cobalt content. When GM introduced the 2017 Bolt, the cobalt level in the cathode had dropped to about 20 percent. Moreover, the energy inside the battery kept rising. Whereas early lead–acid batteries of the EV1 had offered about 40 watt-hours per kilogram, the new breed of lithium-ion batteries was at 250 watt-hours per kilogram. It was a factor of six increase, which translated directly to the range of the vehicle.

At the same time, the supplier community had jumped on board and had squeezed more cost out of their products. Graphite, which was still the status quo for all lithium-ion anodes, had dropped by a factor of almost three. Whereas it had been $15–$20 per kilogram in the days of the Chevy Volt, it was now just $6 for the Chevy Bolt. Current collectors—thin sheets of metal on the electrodes—were now thinner than they'd ever been, which meant that battery makers used less copper and less aluminum. Micro-innovations in electrolytes and solvents pushed costs down even more. And coating machines, which laid the active material on the electrodes, were now faster than ever. Whereas they had once operated at about ten meters per minute, they were now approaching one hundred meters per minute, translating to faster, cheaper production. "That was huge, because now you could look at it and say, 'I'm going to use one-tenth the capital,'" Verbrugge said.

By the time the Bolt was introduced in December 2016, its battery was delivering more range than even GM engineers had originally expected. The Environmental Protection Agency rated it at 238 miles. Its price was $37,495. "Truly the first EV that cracks the code because of long range at an affordable price," Barra said.[55]

At this point, Barra had come to view GM's move to electrification as a nonnegotiable matter. She was deeply committed to battery electric cars. During 2016, she scheduled workshops and strategy sessions at which she delivered her message to GM executives. During one such session with three hundred executives at GM's Proving Grounds, she outlined the company's plans, making her position crystal clear. "We all have to sign up for this plan," she said. Then she signaled toward GM's human resources chief, John Quattrone. "If you don't believe in it, then see John and we'll find a landing spot for you."[56]

The transition to electric cars was neither easy nor fast. Even with the falling cost of batteries, the EV segment grew slowly. When the needle moved from 1 to 1.5 percent in the US, proponents said it had jumped 50 percent, which was true, but the larger reality was that the overall numbers were still miniscule.

By 2020 the electric car market was essentially a Tesla market. In the US, Tesla accounted for nearly 80 percent of electric car sales, and almost half were the Tesla Model 3. Tesla's followers were extraordinarily devoted—cultlike, some said. Devotees were willing to pay high prices for the Model 3, which in theory sold for $35,000 but in reality was closer to $50,000. Still, it was popular. Tesla sold roughly ten Model 3's for every Chevy Bolt. Moreover, three of the country's four most popular pure EVs were Teslas.

For the first time, however, mainstream automakers were not searching for a graceful exit strategy. Despite weak consumer interest, they invested more heavily in electrification. Early in 2020, the consultancy AlixPartners LLP estimated that the auto industry had committed a combined $225 billion to electric car development.[57] And there were good reasons. Governments around the world were committing themselves to phasing out the internal combustion engine. Norway and the Netherlands planned to end IC engine sales by 2025. Germany and India set a goal of 2030. The UK and France aimed for 2040. Brazil, Italy, Canada, Japan, South Korea, and Mexico called for EVs to compose 30 percent of all vehicle sales by 2030. China aimed for 5 percent of sales to be EVs by 2020, and then set up a lottery for those who wanted to buy new gasoline-powered vehicles, making it difficult to purchase them. The international picture was morphing so quickly that any company with global aspirations needed to be prepared for change. Thus, GM, Ford, Volkswagen, Nissan, and all of the other mainstream automakers readied themselves for a new electric era.

The other motivator was the battery. The lithium-ion battery had changed everything. It was cheaper and it packed more energy. And it was still improving. Between 2010 and 2015, GM had amassed a total of 661 US patents on battery technology. Engineers were doing what they called blocking and tackling—improving the battery through many small, fundamental innovations. By 2018, GM had more than seventeen hundred engineers whose job it was to work exclusively on batteries and electric cars.[58] At the same time, automakers were ratcheting up production. Tesla built its massive, ten-million-square-foot Gigafactory near Reno, Nevada, then launched work on another in Shanghai. GM announced an investment of $2.3 billion in a joint venture with LG Chem to build electric car batteries at an Ohio manufacturing facility that would be the size of forty football fields.

They were laying the foundation for a revolution. While Tesla and GM launched manufacturing facilities, Ford raised its investment in electric cars to $11 billion, rolling out its electric Mustang Mach-E in 2020. At the same time, Volkswagen boosted its investment in electric and autonomous cars to a whopping $86 billion.[59] All of the world's mainstream automakers were now building electric cars or plug-in hybrids using lithium-ion batteries. There was, in a sense, a unity of purpose. All—Audi, BMW, Chrysler, Honda, Hyundai, Jaguar, Kia, Mercedes, Mitsubishi, Porsche, Toyota, Volvo—were doing it for same reason. They were recognizing the international urgency. The transition was vividly evident in the price of Tesla shares, which surged 731 percent in 2020. It was clear that the world was moving in the direction of electrification, and no one wanted to be left behind when it eventually arrived.

For most, it was still a hard road. Profitability in the electric car segment was almost nonexistent. After losing money in twenty-nine of thirty quarters, Tesla finally had four profitable quarters in 2018 and '19. But its ability to turn a profit still depended heavily on regulatory credits—that is, payments from competitors.[60] GM, meanwhile, admitted that it was investing more capital in EVs than in gasoline-powered ones, even though the electrics accounted for less than 1 percent of its sales.[61]

Still, the auto industry forged ahead. In March of 2020, GM announced that its battery cell costs had dropped below the $100 per kilowatt-hour barrier. Its new battery, known as Ultium, could power a sedan for four hundred miles. It was a huge moment for the auto industry, and it was a turning point in the history of the lithium-ion battery. GM wasted no time announcing it to the world. "We'll offer EVs from every brand, in every segment, in every body style, at every price point and in every part of the country," Barra told reporters. She then backed it up by saying that in 2020 GM would reveal four new EVs—a Cadillac, a GMC Hummer, and two new versions of the Chevy Bolt EV. All Cadillacs, she said, would be electric by 2030. Finally, she added that GM would keep pushing lithium-ion costs down *below* the $100 per kilowatt-hour level. Its quantity of planned electric car models now exceeded twenty.

Even for skeptics, it was now almost impossible to dismiss GM's commitment. When the coronavirus raged in the spring of 2020, causing GM to halt vehicle production, the company's commitment grew even more evident. With revenues down, GM pushed back its internal combustion engine updates. All of its EVs, however, remained on track. In June of 2020, with GM reeling from the pandemic, Barra and her team were forced to confront the company's growing expenses in the face of a sales slump. In a conference room with details of GM's proposed vehicles displayed on large digital wall charts, executives debated which future vehicles would have to be cut, which would be delayed, and which could stay.[62] At the meeting's end, all of the EVs were untouched.

So it would go in 2020. At the end of the year, GM again reinforced its strategy, boosting its EV budget by 35 percent to $27 billion. Now, it planned to introduce thirty new EVs by 2025. Two-thirds of them would be available in North America, Barra announced. "We have everything in place to drive mass adoption of EVs and make zero emissions a reality," she told attendees at a Barclays PLC conference in November.[63] Within a year, she added, GM would sell a million vehicles a year in China and the US.[64] By 2040, its Ultium battery would be deployed in five million vehicles a year.[65]

Not everyone was on board with this vision, of course. In December of 2020, 150 US Cadillac dealers exited the brand rather than try to sell EVs. Sales were uncertain, they said. More, EVs required about $200,000 in dealership upgrades—charging stations and repair tools. It was easier and less risky to depart, they thought. GM did not debate dealers; it simply bought them out, offering them sums of up to $1 million. "The future dealer requirements are a logical and necessary next step on our path toward electrification," a GM executive said coolly.[66] It was similar to the day five years earlier when Barra had pointed to the head of human resources and declared, "If you don't believe in it, then see John and we'll find a landing spot for you." There would be no debate when it came to electrification.

By 2021, it became clear that Wall Street concurred with Barra. Thanks to massive public investments, Tesla surpassed $1 trillion in market value.[67] Similarly, EV startup Rivian Automotive Inc. overtook GM in market value and Lucid Group Inc. pushed past Ford Motor Company,[68] despite having produced only a relative handful of actual vehicles. Thus, it now became clear that the world saw the electric car and the lithium-ion battery as the future.

More than fifty years had now passed since Joe Kummer had stumbled upon the sodium–sulfur battery. It was forty-eight years since Stan Whittingham's first battery, forty years since John Goodenough's lithium cobalt cathode, and twenty-nine years since Sony had introduced the first commercial lithium-ion battery. Billions of cell phones and tablets now employed lithium-ion. Battery sales were up to $30 billion annually. And now, finally, lithium-ion appeared on the brink of breaking into the transportation industry in a much bigger way, a way that would make all previous sales look small by comparison. The potential production and sales increases were almost incalculable (because one Tesla Model S battery pack used the equivalent of about eighty-five hundred batteries from an iPhone 10).[69] Moreover, the batteries were still improving, the chemistries were changing. Much of the auto industry was using Thackeray's NMC, Chinese automakers were now employing Goodenough's lithium iron phosphate,[70] and another chemistry called nickel cobalt aluminum (NCA) was being produced in massive quantities by Tesla. Therefore, the market would continue to grow.

To be sure, the auto industry knew that much work remained. Sales were still weak. And there were two infrastructure challenges—charging stations and powerplants. Fast charging still required public stations, which were scarce, and utilities weren't truly prepared if the world suddenly flipped a switch and went all electric.

But the auto industry was now so invested in electrification that it was hard to imagine a reversal. The ship was too big and moving too fast to be turned around.

It was hard to put a finger on the exact moment of change. But engineers at GM liked to point to the day when Mark Reuss had declared that the $100 per kilowatt-hour barrier was in view. “I myself was surprised,” Mark Verbrugge said a few years later. “I look back on it and say, ‘My God, I just didn’t think we were ever going to get here.’”

10

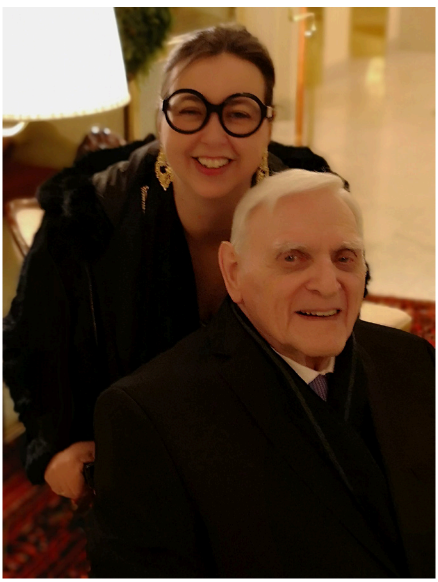
Validation: The Nobel

When the news broke of his life-defining event, John Goodenough could not be reached. He was forty-nine hundred miles from his Texas home at that moment, napping in a London hotel. No one from the University of Texas knew of it yet, since it was the middle of the night in Texas. Worse, Goodenough did not own a cell phone—an irony, given the fact that billions of cell phones were critically dependent on his battery technology.

Thus, when the announcement about the Nobel Prize in Chemistry was made, much of the world learned of it before John Goodenough. It was October, the time of year when the Royal Swedish Academy of Sciences typically published the names of its Nobel laureates. But Goodenough and the other inventors of lithium-ion had expected to be Nobel candidates virtually every year for the past decade and, year after year, nothing had ever come of it. Goodenough had decided at some point not to dwell on it, to move forward. If it happened, it happened. He was ninety-seven now. Besides, he'd been honored with so many major awards. He was the recipient of the Enrico Fermi Award and the Draper Prize, considered the "Nobel of engineering." He'd been presented a National Medal of Science by President Barack Obama. He was a member of the National Academy of Sciences, the National Academy of Engineering, the French Academy of Sciences, the National Academy of Sciences in India, and the Fisicas y Naturales of Spain. He was a known as a scientific giant worldwide, and now he was in London to receive the Royal Society's Copley Medal, the world's oldest scientific award, dating back to 1731.

He found out about the Nobel through Maria Helena Braga, a colleague from the University of Porto who'd collaborated with Goodenough on scientific papers. Braga had flown from Portugal to London to meet with him to discuss some of their recent work and was staying in the same hotel. That morning in London, when it was still dark in Texas, Braga received a text message on her cell phone. It said only, "Ganó!" She immediately knew what it meant. Her twenty-year-old son in Portugal was preoccupied with the possibility that Goodenough might win the Nobel and was constantly checking news feeds on his phone while he rode the Porto Metro, a public transport train. In Portugal, Goodenough was big news. So when Braga's son saw the Nobel decision on his phone, he jumped from his seat and cheered. A fellow rider actually asked him if he'd won the lottery.

When Braga got the message, she ran through the hotel to Goodenough's room, then asked a member of the Royal Society to open his door. "Wake up! Wake up!" she yelled. "You just won the Nobel Prize!" She explained he'd been one of three who'd won for their work on lithium-ion, along with Stanley Whittingham and Akira Yoshino.



Maria Helena Braga with John Goodenough at the Nobel Prize ceremonies in 2019. (PHOTO COURTESY OF PROFESSOR MARIA HELENA BRAGA, UNIVERSITY OF PORTO.)

Goodenough sat up, still groggy. "He had a moment of not knowing what it really meant," Braga said. "He was in shock. He was talking, but the impact . . . it takes time."

There would be a flurry of calls and interviews—The Royal Swedish Academy, British media, Portuguese media, American media. Goodenough handled them gracefully.

He'd been a scientist for seventy years at this point. He had coinvented lithium cobalt oxide forty years earlier, lithium manganese oxide thirty-eight years earlier, lithium iron phosphate twenty-four years earlier. He had watched his chemistries fuel the electronics boom and spark the beginning of an automotive revolution. The dyslexic child of ninety years earlier was now the oldest recipient in the history of the Nobel Prize.

Still, upon hearing the news, he said little. It had been a long road.

The irony of John Goodenough's Nobel win was that he had spent the previous few years trying to put lithium-ion in his rearview mirror.

Over the years, Goodenough had concluded that electric autos needed a better battery chemistry. Lithium-ion, he said repeatedly, wouldn't cut it in the long run. "Right now, lithium-ion batteries rely on a mature technology that doesn't quite make it for the electric car market," he told the electronics engineering magazine *EE Times* in 2012.[1] In 2018, he repeated his belief that lithium-ion wasn't up to the task. "If you charge fast with a liquid electrolyte and a carbon anode, you get dendrites," he said. "And then you get problems. Today, the solution is to charge overnight. But with an electric car, you don't want to have to charge overnight. You want to drive up and get charged in ten minutes."[2]

Even after blazing the lithium trail for forty years, after inventing or coinventing three of the five lithium-ion cathodes, John Goodenough was not satisfied. He was less concerned about the awards, or about his place in history, than about the future of battery technology. So instead of basking in the glory of his successes, Goodenough kept toiling away at the science.

He believed the long-term solution lay in solid-state batteries—that is, batteries with solid electrolytes. That was what connected him with Maria Helena Braga. Braga possessed a spirit akin to Goodenough's; she had the same passion for science, the same openness and innocence toward new ideas. But she never imagined that her signature research work would involve a collaboration with John Goodenough.

Braga had grown up in Porto, a town of about a quarter million on the west coast of Portugal. She had gone to elementary school in Porto, high school in Porto, and then earned her bachelor's and PhD degrees at the University of Porto. She came from simple beginnings. Her parents were not scientists or engineers. Neither had college degrees. When she was growing up, her father ran a toy shop along one of the main avenues of downtown Porto and her mother worked in a tourism office. She hadn't attended private boarding schools, nor had she had a fast-track science education, but she had always been a good student. Then, at age fifteen, she'd read a book titled *Patience dans l'azur: L'evolution cosmique* by noted French physicist Hubert Reeves (translating roughly to "A little bit of blue: The evolution of the cosmos"). It was about the story of the universe, but it wasn't the cosmos that appealed to Braga. Rather, it was the concept of entropy, a subtopic of the book, that intrigued her. It was an unlikely topic for a fifteen-year-old's obsession, but that didn't matter to her. "I loved entropy," Braga said many years later. "I still love it, and I really don't know why." Braga thus sent Reeves a letter full of scientific queries and, to her amazement, received a reply at her home a few weeks later. A couple of months later, she met Reeves at a speech he gave in Portugal, posed for a picture with him, and peppered him with more questions about entropy. Thirty-five years later, Braga would still have the picture and the letter. "He was so kind," she said. "I thought all physicists must be like him." From that point forward, she was hooked. Helena Braga wanted to be a physicist. She earned her bachelor's degree in physics in 1993 and her PhD in 1999, nineteen years after John Goodenough had patented lithium cobalt oxide.

Her collaboration with Goodenough started fifteen years later. By that time, she was serving as a professor of engineering physics at the University of Porto. In 2014 she coauthored a technical paper that appeared in *The Journal of Materials Chemistry A*, describing a glassy electrolyte for a lithium battery.[3] Within a day of the publication, her phone started ringing. Battery start-ups wanted to know more. A Stanford University spin-off called QuantumScape, which made solid-state batteries, contacted her by email. Then she heard from an energy company called Pathion Inc. Two of the company's executives flew from California to meet with her in Portugal. They discussed a large sum of money with the university's tech transfer office, returned to California, then flew back again two months later. It was like magic—as if her life had been suddenly transformed into an inventor's dream. She had gone from being a professor in a small, underfunded physics department to the cocreator of a breakthrough technology. "It was a big moment and I was completely unprepared," she would say later. "I was totally naive. The world of science is completely different than the world of business." During their second visit, Pathion executives encouraged her to come work for them. "They said, 'You have to work in a real lab in the United States,'" she recalled. Then they added an enticement. They were collaborating with a team in Austin, Texas, with Professor John Goodenough. They suggested that Braga partner with him.

Thus began Helena Braga's immersion into the world of high-profile battery development. She signed on as a visiting scholar at the University of Texas and made nine trips back and forth from Porto to Austin in one year. In the beginning, she said, Goodenough was skeptical. But as they synthesized material for the glassy electrolyte, and as they tested it, Goodenough's doubts began to evaporate. Ultimately, he told her he wanted to see more. "It was a great moment," Braga said. "It was confirmation of our results."

By 2016 Goodenough was fully on board. They began making batteries—coin cells and small pouch cells. They tested them hundreds of times, finding that they could be recharged in minutes, rather than hours. Moreover, cycle life—the ability to charge and recharge the battery—was hitting twenty-three thousand cycles. Braga and Goodenough began collaborating on papers and patents. In 2016, she and Goodenough filed for a patent on "water solvated glass amorphous solid ionic conductors." Then they coauthored a paper, "Alternative Strategy for a Safe Rechargeable Battery,"[4] and followed with another paper, "Batteries for Electric Road Vehicles."[5]

Still, it wasn't easy. Their concept was unconventional and it claimed, at least in theory, to be superior to lithium-ion. It sounded improbable. Some of the scientific journals thus preferred to play it safe. The papers were rejected, repeatedly. Even the name of John Goodenough as an author didn't necessarily help.

By this time, the story was trickling out to the popular press. Consumer media, of course, had fewer reservations about the technology than scientific journals. Goodenough's name made it so. The articles were fair and, at first, unflinchingly optimistic. The digital publication *Nova Next* declared that for John Goodenough "lightning appears to have struck twice."[6] *IEEE Spectrum* suggested that Goodenough's "solid-state battery could pose a threat to the internal combustion engine."[7] *Clean Technica* asked, "Has John Goodenough finally done it?"[8] And the *New York Times* suggested that if the battery works as promised, "it would revolutionize electric cars and kill off petroleum-fueled vehicles."[9]

It didn't take long, however, before the flip side of publicity reared its ugly head. Prior to this new concept, there'd been thousands of battery ideas that had come and gone quietly. One day they'd looked promising, and a year or two later they'd disappeared like a stone in the ocean with no fanfare. Not so with

Braga and Goodenough's solid-state battery. In 2017, with publicity at its peak, fellow scientists had begun weighing in. "If anyone but Goodenough published this, I would be, well, it's hard to find a polite word,"[10] noted Daniel Steingart, a professor at Princeton University. Scientists pointed to several problems, including a dielectric constant that seemed too high and the claim that its capacity seemed to grow with repeated cycling. "It's kind of like cold fusion," battery pioneer Jeff Dahn had said. "Here is an experiment that is unbelievable."[11] As the controversy grew, Goodenough made himself available to answer questions on the social media website *Slashdot*, but afterward the criticism was tamped down only slightly.

Ultimately, though, Goodenough simply didn't care about the criticism. He didn't expect immediate gratification. He'd been rejected before. He knew that if the concept had value, success would take time. He wasn't in a hurry. Thirty-eight years earlier, the battery community had ignored his lithium cobalt oxide. And now, as then, he didn't expect to make billions of dollars. He was ninety-six, didn't need the money, and wasn't worried about his legacy. As he had throughout his career, he saw his role as one of service.[12] Seventy years earlier, he'd applied for a Fulbright scholarship to study theology in England. When he'd been rejected and had received a note admonishing him to continue on in physics, he had considered it a sign. Physics *was* service. And that's the role he was playing now—the scientist as missionary.

For her part, Braga remained confident. "We've made hundreds and hundreds of cells, and in all of them we could see the capacity increasing," she said later. "I'm almost sure that one day people will realize this is the way to go."

A year later, the controversy subsided, and Goodenough received word that he'd won the Nobel. He traveled across the world, donned a tuxedo, and appeared on stage to receive the award from the King of Sweden.

Friends, however, couldn't help but feel that a successful solid-state battery would have made him happier.

For the battery community, the 2019 Nobel Prize in Chemistry was a long time coming. Starting in about 2005, scientists had begun lobbying, making the case for a lithium-ion Nobel. Some wrote autobiographies as a way of keeping their names in the running. Others wrote histories for inclusion in scientific journals, prominently mentioning favored candidates.

It was almost impossible to adequately describe the importance of it. In a conventional business, a man or woman with soaring ambition might rise to the level of CEO, or start a company, and cash in along the way. But the life of researchers was different. They often remained in the lab throughout their careers; very often the lab was part of a university or government agency. Mostly, they did not "cash in," as businesspeople did. That was why the Nobel in particular took on an outsized importance. It was their ultimate payoff. The Nobel was the biggest of all awards. Whereas other major scientific awards were known exclusively among scientists, the Nobel was broader. There was the cash part of it, of course—roughly $1.1 million to be split among the recipients. But there was more to it than that. The Nobel was a form of worldwide recognition, not only among scientists but among the general public. Everyone knew the name Nobel. Newspapers in virtually every country, which would ordinarily not a print a word about a scientific award, published front-page stories about the Nobel.[13]

The only problem in the case of the lithium-ion battery was in identifying three or fewer people to receive it. It had to be no more than three, such was the rule of the Royal Swedish Academy. But lithium-ion was so complex, its story so vast. There were solid candidates from Asia, Africa, Europe, and North America. Candidates who had created anodes, cathodes, electrolytes, and entire batteries. John Goodenough was certainly a leader for his work on cathodes, and so was Mike Thackeray and Jeff Dahn. Michel Armand and Rachid Yazami were key figures in the development of graphite anodes, but so were Samar Basu, J. O. Besenhard, and Hiroaki Ikeda. Then there was the battery itself. Stanley Whittingham had been among the first to build a working version of an intercalation battery, but it hadn't been commercially successful. Akira Yoshino and Yoshio Nishi had created commercially viable batteries, but there was some question as to who'd been first. Moreover, Yoshino had labored over it with others at Asahi Chemical, most notably Kenichi Sanechika and Takayuki Nakajima, and there was an issue of who did the work. Finally, there was the issue of geopolitics. Europeans, Japanese, and Americans would presumably be angered if their geographic regions were left out. Thus, the list kept getting longer, and the choices more complex.

When it was announced in October 2019 after more than a decade of waiting, the world, of course, never fathomed the complexity of the decision. Goodenough, Whittingham, and Yoshino had won. Significantly, the trio of winners met the geopolitical requirement. Goodenough was American, but had made his two biggest discoveries while at the University of Oxford in England. Whittingham, originally British, had moved to the US and had done his most important work in New Jersey for Exxon. And Yoshino was Japanese. Three continents, quite appropriately, were represented.

The winners, of course, were delighted. Stan Whittingham, by this time a seventy-eight-year-old professor of chemistry at SUNY Binghamton University in upstate New York, was suddenly vaulted into international prominence. On the day of the Nobel announcement, Whittingham's win was announced at battery conference in Ulm, Germany, and attendees there gave him a standing ovation, then celebrated with champagne after lunch. The mayor of Ulm showed up at the conference to shake his hand, and reporters from the Associated Press and Reuters appeared within thirty minutes to interview him. At the airport on his way home, Whittingham saw his picture on the front page of the German newspapers. His Nobel status was announced at the airline gate and he was quickly upgraded to a first-class seat for his ride back to the US. Within a day, his story appeared in the British newspapers. Back home, there were three front-page stories about Whittingham in a ten-day span, and there was a message of congratulations from New York governor Andrew Cuomo. People on the streets suddenly recognized his face.

No country, however, was more ecstatic than Japan. For at least a week until the story's momentum diminished, Akira Yoshino became the most important person in the nation. There were photos of him smiling broadly, surrounded by hundreds of cheering colleagues, holding massive bouquets of flowers, and they seemed to be everywhere. His beaming face led *every* Japanese TV newscast. The *Mainichi Shimbun*, a newspaper with a three-million-plus circulation, published six stories about Yoshino in a single day.[14] The Prime Minister of Japan, Shinzo Abe, congratulated Yoshino. Japan's public broadcasting system even tracked down the fourth-grade schoolteacher who'd inspired him to read a book titled *The Chemical History of the Candle*, which had laid the foundation for his interest in science.[15] The teacher was in her eighties and did not remember Yoshino, but it didn't matter. No detail about Yoshino's life, it seemed, was too small to include in the wake of the award.

The world's scientific intelligentsia, however, was not as giddy about the Nobel decision. A week after the announcement, retired Sony engineer Yoshio Nishi held a press conference to express his dissatisfaction at being left out.[16] He pointed out that Sony had been first to market with the lithium-ion battery; indeed, it was generally accepted that Sony had coined the term "lithium-ion." He explained that Sony had made the decision to use a "soft" carbon anode and had brought it to market ahead of everyone else. He did not seem to have an issue with the selection of John Goodenough. His special grievance was reserved for his own countryman. "I'm not sure where the recognition that Asahi Kasei is the first to do the same thing comes from," he said.[17] The *Mainichi Shimbun* even stepped in on Nishi's behalf, stating that Japanese science journalists had expected him to win. The newspaper had conducted interviews and "prepared a manuscript that could be reported immediately after the announcement." The newspaper's editors were that sure of a Nobel victory. When the moment arrived, however, they and Nishi had been badly disappointed.

In Morocco, journalists asked why their countryman, Rachid Yazami, had been forgotten. The *Morocco World News* argued his case, explaining that the academy had called the winners on cell phones that employed "his" graphite anode.[18] Ultimately, the newspaper concluded that the academy's rationale had been more theoretical than practical.

Others asked why Michel Armand or Michael Thackeray had not been chosen. Armand, it was said, coined the term "rocking chair battery." He had also been an early proponent of graphite electrodes and had contributed mightily to the existence of a practical lithium iron phosphate cathode. Thackeray, meanwhile, had played a critical role in the development of two of the world's five different cathode materials. His lithium manganese oxide (LMO) cathode was used in handheld power tools and medical devices around the world, and his nickel manganese cobalt chemistries were, by this time, the fastest-growing automotive powertrain.

The truth, though, was that the task of boiling the list down to the three most important developers had been virtually impossible. The lithium intercalation battery had been an idea in the air. Hundreds had contributed and much of the history had been clouded by secrecy. Although the modern world had grown accustomed to the lone inventor concept, it was largely a myth, particularly in the case of the lithium-ion battery. The lithium-ion battery was not the product of a single mind; it was the product of many, many minds. It had been built by thousands of small insights gleaned from papers, lab reports, and conferences from around the world over half a century. It was truly a global battery.

No one contested the awarding of the Nobel to John Goodenough. There were many reasons for this. The volume of his work was immense, and he'd been a major contributor on three of the five cathodes used in lithium-ion batteries. Then there was his length of service. He'd spent roughly seventy years in physics and had been in the lithium-ion battery field for forty years. Most of the battery community, knowing that the Royal Swedish Academy would not award a Nobel posthumously, had been happy that he'd lived long enough to be a recipient.

The American media, of course, was even happier. It loved the story—the ninety-seven-year-old professor, still toiling away until he'd won the Nobel. All at once, the world knew of his achievements. He was profiled by all the major US news outlets, including the *New York Times*, *Wall Street Journal*, *USA Today*, *Boston Globe*, *Chicago Tribune*, *Dallas News*, *Washington Post*, *Japan Times*, *India Times*, CNN, and NPR. Even Dyslexia.com did a story. Those who knew Goodenough believed he was slightly uncomfortable with it all. He understood better than anyone how many scientists had contributed to the battery over the course of fifty years and did not consider himself a lone inventor. But his story was so good and the battery community so supportive that it was easier for the media to tell the tale through him. The stories were at once informative and touching, the kind that readers could easily wrap their minds around. They were about the invention of the lithium-ion battery, and the ninety-seven-year-old man behind it.

When he returned to Texas from London after collecting the Copley Medal, a police detail met him at the Austin airport. University of Texas officials, knowing that photos of him were now on the front pages of newspapers around the world, had feared that he would be mobbed at the airport. Austin police escorted him back to his home.

At ninety-seven, Goodenough was science's new rock star. Scientists, as a rule, generally toiled in obscurity, but now that rule was changing. Congratulatory messages poured in from around the world, from friends and scientists, from alumni at the schools where he'd served, from politicians and dignitaries, and even from pop culture figures, including actor Matthew McConaughey, who had tweeted "huge congrats." Never had a materials scientist roused such attention.

For many, the most captivating aspect of Goodenough's story was that he was still working. It would have been a different story if he'd been drawn from a decades-long retirement to make a final, feeble public appearance, but that hadn't been the case. Here he was, still working, *thirty-two years* after the University of Oxford had tried to retire him. He was still a familiar figure in the halls of the engineering school at the University of Texas. He regularly attended faculty meetings and spent lab time laboring over his next battery breakthrough. Still trim, he had a full head of white hair, bushy white eyebrows, and deep-set blue eyes. Befitting his age, he used a walker for locomotion and a wheelchair for longer treks. But colleagues said he was still mentally sharp. And he worked hard. Asked once by a reporter if Goodenough still worked an eight-hour day, assistant Melissa Truitt-Green had responded, "No, sometimes he works ten hours."[19]

Goodenough's life was simple. His wife, Irene, had passed away three years earlier. They'd had no children. His family was the university—the other professors and researchers. His kids were his grad students and postdoctoral fellows. He loved the place. He awoke every morning at 5:30 a.m., ate breakfast, and, until the last few years, had driven himself to work. At the Cockrell School of Engineering, he was considered a sort of eminence. Colleagues said they'd listen for his characteristic high-pitched laughter echoing down the hallways and they'd know he was there and that all was well. He worked every weekday and most weekends. He shared his home with a couple from the university who worked with him and who drove him back and forth to the lab every day. Typically, he turned in by 9:30 p.m., slept his eight hours, then lived to work another day.

At the Nobel ceremonies in Stockholm in December 2019, the attention went on, unabated. On the streets, Goodenough was at the center of the action. Groups of young people sidled up to him, requesting autographs and selfies. They wanted their minute with the science world's new rock star. Later, in the packed concert hall, where attendees wore gowns and tails, where Nobel-winning physicians and economists and scientists gathered, Goodenough was still the biggest story. When aides pushed his wheelchair onto the stage and he shook the hand of Sweden's king, he was met with "a roar of sustained applause that reverberated throughout the hall," wrote a University of Texas publication.[20]

It was impossible to stop. Even though two other men had shared the chemistry Nobel with him, the media attention naturally fell upon Goodenough. His was the watercooler story—the ninety-seven-year-old man who won a Nobel for a discovery he'd made forty years earlier, the inventor who toiled in obscurity for nearly seventy years, the scientist who as a child seemed slow because he was dyslexic, the professor who was forced into retirement but changed jobs and worked for thirty-two more productive years, ultimately winning a Nobel. With each new telling, his story seemed to get better.

Moreover, the science behind Goodenough's accomplishment seemed so accessible. Too often, Nobel-level science involved almost incomprehensible topics—radiation, spectroscopy, magnetism, atomic structure, quantum mechanics. But Goodenough had helped create something the world could understand—a battery. This wasn't a story about muons in a particle accelerator; it was about something you could hold in your hand. It was about a device that virtually every person outside the third world had owned and operated. And it was about an aging professor who'd made a major contribution to the device and transformed the world.

As compelling as his story was, however, Goodenough was glad when the attention subsided. He knew he wasn't the lone inventor; he knew how many scientists had been involved in lithium-ion. Upon returning from Stockholm, he took two months to rest. He gathered his energy again, planning his return. He began considering his ongoing research. He thought about his grad students and his postdocs.

It was time to get back to work.

Afterword

What History Teaches Us

If there's a single lesson in the history of the lithium-ion battery and the electric car, it's this: Technologies evolve at different rates.

As this book reaches publication in fall of 2022, Stanley Whittingham's concept for the rechargeable lithium battery will be fifty years old. Similarly, John Goodenough's lithium cobalt oxide cathode will be forty-two years old. By now, those two scientists would have almost certainly expected their ideas to be more broadly adopted by the auto industry, or to have been washed away by time. They couldn't have foreseen that the rechargeable lithium battery would still be struggling for a sliver of the automotive market. Nor that the personal computer, cell phone, flat-screen television, and Internet, all of which came later, would have breezed past the lithium-ion EV battery in market penetration.

The lithium-ion battery was slower than those technologies because its evolution was a function of chemistry and thermodynamics. Its economies of scale were unrelated to the pace of semiconductor development. That fact alone seems to have to have puzzled the world—don't all modern technologies follow the pattern of flat-screen televisions? No, they don't. And that was the case for lithium-ion. It evolved at its own pace. Moreover, its success was constrained by a long list of predecessors that failed to live up to their hype. Batteries, it seemed, were not to be trusted. Thus, the world had to experience lithium-ion to believe in it.

That was especially so in the world of electric vehicles. Whereas lithium-ion made rapid early gains in electronics, its adoption in the automotive world called for it to vie with the century-old gasoline engine. And the engine, dirty and inefficient as it was, turned out to be a formidable competitor. Gasoline's energy density was easily twenty times that of lithium-ion's, even when accounting for inefficiencies. Moreover, its infrastructure was firmly established. And its convenience—in the form of a five-minute refueling time—was unparalleled. Those qualities made the gasoline engine almost impossible to dislodge, even when the world clearly recognized its downside.

Many more challenges still lie ahead. The growth of lithium-ion-powered vehicles will be influenced by cost and performance. That's a given. But growth will also be affected by forces outside the battery lab, just as in the past. We now know that infrastructure, government edicts, and unpredictable consumer preferences can turn rosy forecasts upside down. Electrical grid capacity can also be a challenge. If we flipped a switch and went all-electric today, more grid sources would be needed, and that, too, would take time.

Moreover, there's the unknown of emerging technology. There may be an up-and-coming chemistry in a lab right now that will one day supersede lithium-ion. No one knows. But even if that's the case, there is a chance that its evolution and adoption may be as slow as that of lithium-ion. Thus, history suggests that decades could pass before the next great competitor emerges in a big way.

That's why many experts believe that lithium-ion could still be around at the dawn of the next century. "Lithium-ion will keep advancing," notes Michael Thackeray, coinventor of the lithium manganese oxide cathode. "And every advance that it makes, however incremental, makes it more and more difficult for any competing chemistry to come into play."

Acknowledgments

I decided to write this book in the fall of 2019 because I believed that the difficulty of bringing a battery-powered car to market was vastly underappreciated. It was a story that I thought needed to be told. As it turned out, however, I was the one who didn't fully understand how complex this story was. Far more people in more organizations around the world played key roles than I had ever imagined.

I owe an immense debt of gratitude to the following people who helped me understand the technical breadth of this complex story and who generously read and critiqued early drafts of this book: Dr. Brian Barnett of Battery Perspectives LLC, who advised me, generously supplied background material, connected me to scientists in the US and in Japan, and took countless calls from me; Dr. David Cole of the Center for Automotive Research and the University of Michigan, who tutored me and critiqued my work; Dr. Ron Radzilowski, formerly of Ford Motor Company, who taught me about the early years of fast ion transport at Ford; Dr. Michael Thackeray of Argonne National Laboratory, who spent many hours on the phone with me explaining the nuances of battery history; and Dr. Kang Xu, fellow of the Electrochemical Society, who meticulously combed through my copy and patiently advised me.

Sincere thanks also to my friends Michael Bartlett, who encouraged me to do this book, and George Leopold, Larry Maloney, and Rob Spiegel, who offered valuable comments and made my jumbled prose more readable. Also to Richard Colella, an engineer and Tesla owner who graciously agreed to comment on the eighth and ninth chapters.

Special thanks to my family: Pat Murray, my wife, for her wise and patient reading of the manuscript, as well as Tim Murray, Erin Murray, Joe Murray, Dan Murray, and Mary Ellen Moriarty, who graciously read the copy and listened to my ramblings for two years.

Gathering information in the era of COVID was particularly difficult and required many hours of phone conversations and emails with individuals who had never met me. I sincerely thank the following people for sharing their insights, big and small, and for trusting me: Matt Andres, Dr. Michel Armand, Lance Atkins, Ken Baker, Dr. Maria Helena Braga, Joseph Burba, Dr. George Blomgren, Dr. Elton Cairns, Dr. Jeff Dahn, Dr. Bill David, Dr. Richard E. Dyck, Dr. Matthew Dzieciuch, Dr. Russell Egdell, Tom Gage, Dr. Kevin Huang, Dr. Robert Huggins, Dr. Frank Jamerson, Dr. Arden Johnson, Dr. Hadi Khani, Dr. Isao Kuribayashi, Grady Loy, Dr. Bill Macklin, Dr. Arumugam Manthiram, Dr. Nikola Marincic, Dr. Ted Miller, Dr. Koichi Mizushima, Dr. Aisaku Nagai, Takayuki Nakajima, Les Nichols, Dr. Henry Petroski, Dave Piontek, Dr. Donald Sadoway, Milda Saenz, Roger Schreffler, Dr. Vaclav Smil, Dr. Walter van Schalkwijk, Dr. Mark Verbrugge, Tom Watson, Dr. Neill Weber, Dr. M. Stanley Whittingham, Mary Ann Wright, Dr. Rachid Yazami, and Dr. Heng Zhang.

Thanks also to those who helped me locate important people and information: Dr. Peter Edwards and Richard Lofthouse at Oxford University, Emma Berg at Ford Motor Company, Phil Lienert at General Motors, Jeff Wandell at Nissan Motor Company, and John Holden of the University of Texas at Austin. Also thanks to Larry Zevnik and Pam Nelson of the Park Ridge Public Library in Illinois, who found obscure Japanese journal articles that I had lost hope of ever locating.

Of the Nobel Prize winners, two declined to be interviewed for this book. Due to the frailty of his health, Dr. John B. Goodenough was not made available for discussions. Therefore, I relied on two previous interviews I had done with him (May 4, 2012, and January 9, 2018), as well as on archived interviews done by California Institute of Technology (2001), the Electrochemical Society (2016), Royal Society of Chemistry (2019), American Chemical Society (2019), and the Royal Swedish Academy of Sciences (2019). I also made use of Dr. Goodenough's brief autobiography, *Witness to Grace*, as well as news accounts and the recollections of colleagues.

Dr. Akira Yoshino also declined to be interviewed for this book, citing a busy schedule due to intense media attention following the Nobel Prize. Thanks to the gracious efforts of Shuichiro Ogawa of Asahi Chemical, however, I was able to send questions to Dr. Yoshino, who responded in brief fashion on several occasions. In addition to those responses, I relied on Dr. Yoshino's book, *Lithium-Ion Batteries Open Doors to the Future: Hidden Stories by the Inventor*. The book was translated from Japanese to English for me by Hiro Tsuchiya of Yamary Language Services in the US. I also relied on many translated accounts from the *Mainichi Shimbun* and on conversations with Dr. Yoshino's former colleagues.

Special thanks to Justin Race, director of Purdue University Press, who had a strong sense of the direction for this book from our very first conversation. Thanks also to Purdue Press's editorial, design, and production team: Kelley Kimm, whose amazing eye for detail saved me from myself more times than I can count, as well as Katherine Purple, Andrea Gapsch, and Chris Brannan for their many valuable suggestions.

Finally, I sincerely thank the Alfred P. Sloan Foundation for its generous support in the research and writing of this book.

Who's Who

Armand, Michel One of the first to suggest the possibility of a graphite anode in a patent. Also a contributor to the lithium iron phosphate battery and originator of the term "rocking chair battery."

Baker, Ken Chief engineer of the GM Electrovette and program manager of the GM EV1.

Basu, Samar AT&T Bell Labs scientist who earned a patent on the graphite anode.

Besenhard, Jürgen Otto Scientist at Munich University of Technology who published an early paper suggesting that metal ions could be inserted into graphite.

Braga, Maria Helena Materials scientist from the University of Porto who worked with John Goodenough on a solid-state battery.

Burba, Joseph Ford powertrain engineer who headed development of the Ecostar electric van, which used sodium–sulfur batteries.

Cairns, Elton Head of electrochemistry at GM Research Labs who spearheaded development of the zinc–nickel oxide battery for the GM Electrovette.

Cocconi, Alan Founder of AC Propulsion and chief developer of the lithium-ion battery that used thousands of tiny cells to power the Tzero electric car. Also the inventor of the inverter for GM's EV1.

Dahn, Jeff One of the first battery developers to suggest the use of the ethylene carbonate (EC) electrolyte. Also one of the inventors of the nickel manganese cobalt (NMC) battery.

Eberhard, Martin Cofounder of Tesla Motors.

Edison, Thomas Legendary American inventor who patented the nickel–iron battery. Teamed with Henry Ford on the development of an electric car using nickel–iron in 1914.

Ford, Henry Automotive legend who teamed with Thomas Edison on an ill-fated electric car in 1914.

Gage, Tom Automotive engineer and race car mechanic who helped develop the lithium-ion-powered Tzero electric car for AC Propulsion.

Goodenough, John Nobel Prize–winning scientist who developed or codeveloped the chemistries for three of five most prominent lithium-ion cathodes.

Hamlen, Bob Battery scientist who headed the manufacturing team for Exxon's lithium titanium disulfide battery.

Huggins, Bob Stanford University materials scientist who pioneered the study of fast ion transport in batteries during the 1970s.

Ikeda, Hiroaki Sanyo battery scientist who began researching graphite electrodes during the 1970s.

Kummer, Joseph Scientist at Ford Motor Co. who suggested the use of the beta alumina solid electrolyte and coinvented the sodium–sulfur battery.

Kuribayashi, Isao Battery scientist and executive who helped steer Asahi Chemical to the development of its first lithium-ion battery.

Marincic, Nikola Materials scientist at Battery Engineering Inc. in Boston who built the first preproduction rechargeable lithium cells.

Miller, Ted Ford battery scientist who helped create early lithium-ion batteries for Ford vehicles.

Mizushima, Koichi Codeveloped the lithium cobalt oxide cathode with John Goodenough at Oxford.

Musk, Elon Physicist and entrepreneur who provided critical early funding for Tesla Motors, then built it into the biggest electric car manufacturer in the world.

Nakajima, Takayuki Asahi Chemical scientist and coinventor of the first petroleum coke carbon anode for a rechargeable lithium battery.

Nishi, Yoshio Sony battery scientist who spearheaded development of the world's first commercial lithium-ion battery.

Ovshinsky, Stan Independent inventor and head of Ovonic Battery Company who codeveloped the nickel–metal hydride battery.

Sanechika, Kenichi Asahi Chemical battery scientist and coinventor of the first petroleum coke carbon anode for a rechargeable lithium battery.

Straubel, JB Tesla Motors' first chief technical officer.

Tarpenning, Marc Cofounder of Tesla Motors.

Thackeray, Michael Battery scientist who codeveloped the chemistries for lithium manganese oxide and nickel manganese cobalt cathodes.

Verbrugge, Mark Battery scientist who helped steer General Motors to lithium-ion batteries.

Volta, Alessandro Italian physicist and inventor of the battery.

Weber, Neill Ford scientist who coinvented the sodium–sulfur battery with Joseph Kummer.

Whittingham, Stanley Nobel Prize–winning battery scientist who developed the lithium titanium disulfide battery at Exxon in 1972.

Wright, Mary Ann Vehicle engineer who pushed Ford to move from nickel–metal hydride to lithium-ion batteries in its EVs.

Yazami, Rachid Early proponent of the graphite anode and one of the first scientists to intercalate lithium ions into graphite.

Yoshino, Akira Asahi Chemical scientist who won the 2019 Nobel Prize in Chemistry for co-development of the first carbon anode.

Glossary

anode Negative pole of the battery.

battery An energy storage device containing cells that generate electricity from chemical reactions.

beta alumina Solid electrolyte in Ford's sodium–sulfur battery.

cathode Positive pole of the battery.

EC (ethylene carbonate) electrolyte Liquid electrolyte used in lithium-ion batteries. It succeeded the PC electrolyte because it allowed for the use of the graphite anode.

electric car A car powered solely by electricity from a battery or fuel cell.

electrode An electrical conductor in a battery, either the anode or cathode.

electrolyte A chemical (usually, but not always, a liquid) containing ions between the battery's electrodes.

fast ion transport Fast transport of highly mobile ions, usually in a solid electrolyte.

graphite A form of carbon used as the anode in billions of lithium-ion batteries.

hybrid car A partially electrified car, usually using both a battery and an internal combustion engine.

intercalation Insertion of a molecule or ion into a solid.

ion A charged atom or molecule. It's charged because the number of its electrons do not equal the number of protons.

lead–acid battery Rechargeable battery invented in 1859 by French physicist Gaston Planté.

lithium A chemical element; the lightest metal in the periodic table.

lithium cobalt oxide (LCO) The first of the lithium-ion chemistries. Developed by Nobel Prize winner John Goodenough and Koichi Mizushima in 1980.

lithium iron phosphate (LFP) battery A type of lithium-ion chemistry developed by John Goodenough and Akshaya Padhi at the University of Texas. It originally served in grid storage but has recently gained much popularity in electric cars.

lithium manganese oxide (LMO) The second of the lithium-ion chemistries. Developed by Michael Thackeray and John Goodenough in 1981.

lithium titanium disulfide battery The first of the rechargeable lithium batteries. It was developed by Nobel Prize winner Stanley Whittingham at Exxon Corporation in 1972.

lithium-ion battery A rechargeable battery that inserts lithium ions in the electrodes. It typically uses one of several different lithium compounds at the cathode and graphite at the anode.

nickel cobalt aluminum oxide (NCA) battery A type of lithium-ion chemistry commonly used in electric vehicles, mostly by Tesla Motors.

nickel manganese cobalt (NMC) battery A type of lithium-ion chemistry commonly used in electric vehicles.

nickel–metal hydride battery A battery of the pre-lithium-ion era. Developed by the Ovonic Battery Company in 1986, it served in millions of Toyota Prius hybrids and was briefly used in GM's EV1 electric car.

PC (propylene carbonate) electrolyte A type of liquid electrolyte used in early lithium-ion batteries. It fell out of favor because it did not allow for the use of a graphite anode.

petroleum coke A soft gray carbon material used in steel manufacturing, it served as the anode in Sony's first commercial lithium-ion battery. It was known as the "soft carbon" anode.

primary battery A battery that cannot be recharged. A disposable battery.

secondary battery Rechargeable battery.

silver–zinc battery The original chemistry of Alessandro Volta's voltaic pile in 1800. It later powered GM's Electrovair electric car in 1966.

sodium–sulfur battery Battery developed by Ford Motor Company in 1960s. A so-called solid-state battery, it used a solid electrolyte and molten liquid electrodes.

Zebra battery A high-temperature sodium–nickel chloride battery developed in South Africa in 1985.

zinc–nickel oxide battery The chemistry of choice for GM's Electrovette electric car, announced in 1979.

Notes

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About the Author

Charles J. Murray has written about science and technology for the past thirty-eight years, during which he has published more than five hundred articles on electric cars and batteries. His work has appeared in engineering journals such as *Design News*, *EE Times*, and *Semiconductor International*, as well as in many consumer publications, including the *Chicago Tribune* and *Popular Science*. He is a recipient of numerous editorial awards, and was a cowinner of the Jesse H. Neal Award for business journalism. He holds a BS in engineering from the University of Illinois at Chicago.