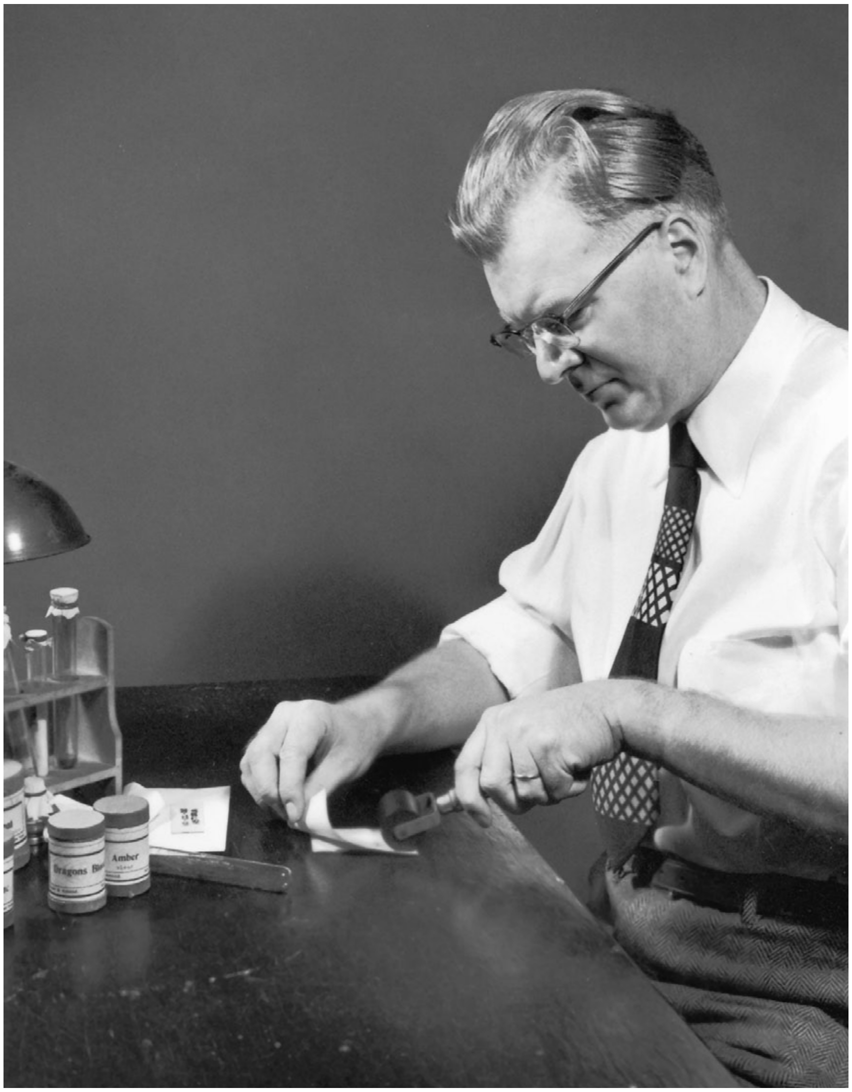
Copies in Seconds

by David Owen



In 1962, Chester Carlson (BS '30) reenacts making the world's first photocopy. (The "dragon's blood" in the vial is a resin, not an alchemical ingredient.) Photo courtesy of the Xerox Corporation.

When Chester Carlson, working in the patent office at P. R. Mallory, needed a copy of a drawing in a patent application, his only option was to have a photographic copy made by an outside company that owned a Photostat or Rectigraph machine. "Their representative would come in, pick up the drawing, take it to their plant, make a copy, bring it back," he recalled later. "It might be a wait of half a day or even twenty-four hours to get it back." This was a costly nuisance, and it meant that what we now think of as a mindless clerical task was then an ongoing corporate operation involving outside vendors, billing, record keeping, and executive supervision. "So I recognized a very great need for a machine that could be right in an office," he continued, "where you could bring a document to it, push it in a slot, push a button, and get a copy out."

As Carlson began to consider how such a machine might work, he naturally thought first of photography. But he realized quickly that photography had distressingly many inherent limitations. Reducing the size of a bulky Photostat machine might be possible, but a smaller machine would still require coated papers and messy chemicals—the two main reasons making Photostats was expensive and inconvenient. Photography, furthermore, was already so well understood that it was unlikely to yield an important discovery to a lone inventor like Carlson. People had been using cameras for more than a century, and the laboratories at Eastman Kodak were filled with well-financed researchers, yet no one, so far, had come up with a method of making photographic prints on ordinary paper. Carlson reasoned that silver halide photography almost certainly did not hold the solution to the copying problem—and that if it did somehow hold the solution, he himself would be highly unlikely to find it.

Having eliminated conventional photography as a field of investigation, Carlson next considered the possibility of making copies chemically—perhaps by using a mild solvent to partially dissolve the text or image of an existing document, so that an impression of it could be made by pressing a blank piece of paper against it, as with a copying press. But there are hopelessly many different writing and printing media—water-based inks, oil-based inks, graphite, charcoal, crayon, and others—and Carlson knew that no single solvent would work with all of them. Besides, even if a single practicable solvent could be found, using it would unavoidably harm the original document, and the reproduced image would be reversed, like a reflection in a mirror. Chemistry alone, he decided, could not provide the answer.

If ordinary photography was messy, and chemical processes ruined originals, what was left? "The only thing common with the different inks, pencils, and papers is that they reflect light in different ways from the image areas and from the background areas," he said later. We easily distinguish text from the paper it's printed on, because the ink absorbs most of the light that strikes it (and therefore appears black), while the paper reflects the light (and therefore appears white). A nondestructive copying process, Carlson reasoned, would almost certainly have to take advantage of this contrast—just as conventional photography does. But how? Were silver halides the only materials that changed when exposed to light? Carlson went back to the library and soon found a book called *Photoelectric Phenomena,* which had been published a few years before.

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Photoelectricity is so hard to understand that Albert Einstein won the Nobel Prize in 1921 for having explained it in 1905. (Incidentally, Einstein, like Carlson, was a physicist who worked in a patent office.) To simplify a great deal, a photoelectric material is one that sheds electrons when light shines on it. The phenomenon was first noticed in 1887 by the German physicist Heinrich Hertz (whose name is preserved in the standard scientific term for "one cycle per second"). Hertz observed that the sparks thrown off by an induction coil in his laboratory got smaller when he darkened the room (as he had done in the hope of seeing the sparks better). Einstein's explanation, which became part of the basis of quantum mechanics, was that when light, behaving like a stream of particles, collides with electrons on the surface of a photoelectric material, it knocks significant numbers of the electrons loose and thereby stimulates increased electrical activity: bigger sparks. A related phenomenon is photoconductivity, which Carlson read about in the same book. A photoconductive material is one whose ability to transmit electricity increases when it is illuminated. This happens because light, behaving like a stream of particles, jostles the electrons on the material's surface and thereby increases the material's ability to conduct a charge.

Carlson realized that if he could devise a copying process based on voltage rather than amperage, he might be able to build a machine that would neither set paper on fire nor electrocute its operator.

"I thought that if a layer of photoconductive material could be placed in contact with a sheet of paper that had been wetted with a chemical, the paper would change color if electricity flowed through the sheet," Carlson said later. Working in the kitchen of his apartment, he saturated a sheet of ordinary paper with a solution of potassium iodide and starch, placed the treated paper on a copper plate coated with cuprous oxide (a photoconductor), placed a printed document on top of the treated paper, and shone a bright light through the back of the document. As he explained on another occasion, he was hoping that the sheet of paper "would be darkened by the photoelectric currents that I thought would be produced during exposure," and that an image of the printed document would form on the treated paper. But nothing happened.

"That led me to take a somewhat deeper look into the needs of the process," he recalled in 1964; "e.g., I recognized that photoelectric currents are bound to be rather small, but, on the other hand, electrochemical effects which I was trying to use require rather large currents to cause any substantial darkening of a layer."

Furthermore, a current large enough to darken paper would also most likely be large enough to set it on fire, among other undesirable results. He concluded that his idea was "even less satisfactory than the known photographic methods that were then used," and turned his attention from amperage to voltage. "With high voltage, the current could be small but still the energy could be high," he realized. "This led me to the idea of electrostatics."

Electrical phenomena are conventionally divided into two broad and confusingly overlapping categories: current electricity and static electricity. Current electricity is what makes electric appliances work; it consists of continuously flowing electrical charges. Static electricity is what causes your hair to stand up when you run a plastic comb through it; it consists of opposite electrical charges that are separated or imbalanced (and that produce transitory electric currents—sparks, lightning—when the voltage is sufficient to ionize the air separating them). Scientists have been known to come to blows over these definitions. For the purposes of understanding xerography, it's enough to say that the most important difference has to do with amperage, which can be thought of as analogous to volume in the flow of water, and voltage, which can be thought of as analogous to water pressure. Generally speaking, an electric current involves relatively high amperage at relatively low voltage, while electrostatic phenomena involve high voltage at low amperage. (The electric current you experience when you stick a butter knife into a wall receptacle is just 110 volts, but it's more than enough amps to kill you; the harmless electrostatic shock you receive when you shuffle across the carpet and touch a metal doorknob is many thousands of volts but virtually zero amps.)

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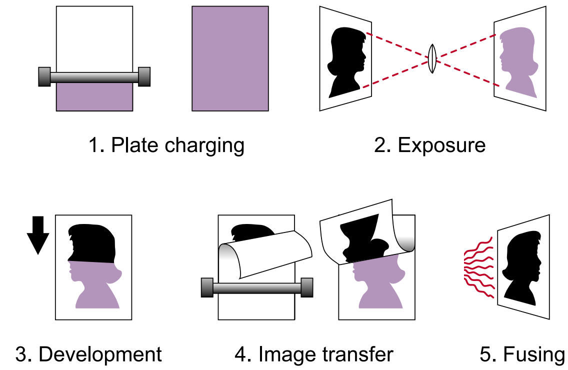
Carlson returned to the library. And there, while working his way through a pile of foreign technical journals, he came across a brief article by a Hungarian physicist named Paul Selenyi. Selenyi had been trying to devise a way of transmitting and printing facsimiles of graphic images, such as news photographs. His method, which he had tried with some success, involved using a directed beam of ions to lay down a patterned electrostatic charge on the outside of a rotating drum that was covered with an insulating material—something like the way a cathode ray tube creates a picture on a television screen, by scanning a beam of electrons repeatedly across it one line at a time, or like the way an ink-jet printer sprays ink in an intelligible pattern onto a sheet of paper.

"He had developed, essentially, a triode in air," Carlson said later. "It embodied a heated cathode enclosed in a metal cup which had a small hole in it. Then there was a drum coated with hard rubber or some kind of insulating varnish that rotated very close to that hole. The heated cathode created ions within the metal cup and the metal let varying proportions of ions through a little opening. They were deposited on the rotating, insulating drum by a bias field that was applied. Then, after the image had been scanned, he simply dusted the drum with a fine powder and the image became visible." The powder stuck to the ions on the insulating surface of the drum in the way that beach sand sticks to wet spots on a bathing suit. A transmitted photographic image that Selenyi had generated in this manner was reproduced in the journal; it was grainy, and the scanning lines were quite noticeable, but the image was reasonably distinct.

Using finely divided powders to make visible images of electrostatic charges was an old idea in physics; it had first been done in 1777, when George Christoph Lichtenberg, a German professor, noticed that house dust adhered to an electrostatically charged piece of amber in a distinctive arrangement, which later became known as a "Lichtenberg figure." Carlson knew about Lichtenberg figures, and Selenyi's work reminded him of them. Suddenly, he saw that he might be able to make copies by employing a similar phenomenon in combination with photoconductivity. Instead of trying to use light to generate an electric current in a sheet of paper placed on top of a photocon-

The creative spark: Static electricity allows you to play with very high voltages but very small currents—this plasma ball has a couple of thousand volts running through it, but only about one amp.

Carlson's senior picture in the *Big T*, the Caltech yearbook. Carlson, who grew up in the San Bernardino area, entered Caltech after graduating from Riverside Junior College in 1928. Upon receiving his BS in physics, he took an engineering job at Bell Labs and moved to Manhattan. He soon transferred to the Lab's patent office, from which he was fired in 1933. He married Elsa von Mallon in 1934 before taking up the quest for xerography in earnest in 1937; the strain contributed to their divorce in 1945.



How xerography works: A specially prepared plate is charged with static electricity (purple). The charge drains away wherever light hits the plate; dark areas remain charged. A black powder of opposite charge will stick only to those areas, and when a piece of paper is pressed against the plate the powder (and the image) is transferred. Heat treatment binds the powder to the paper.

ductor, as he had done in his kitchen experiments, he would use light to remove electrostatic charges from the nonimage areas of a uniformly ionized photoconductor. Then he would make the pattern visible by dusting it with powder, and transfer the powder to a sheet of untreated paper.

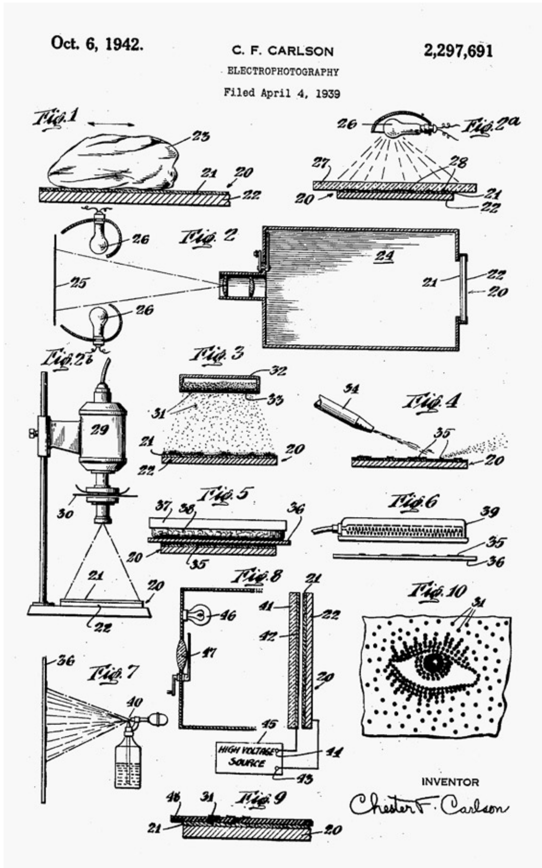
Photoconductivity was the key. Carlson knew he needed to find a material that would act as an electrical conductor in the light and as an electrical insulator in the dark. If a grounded metal plate coated with a thin film of such a material could, in the dark, be given a uniform electrostatic charge—perhaps by using an electrostatic generator to spray ions onto its surface—then exposing the plate to light should cause the charge to drain away. And if that light could be shone on the charged plate not uniformly but in the image of a printed page, then the charge should drain away only from the illuminated parts of the plate (the parts corresponding to the reflective white background of the page) and persist in the parts that remained dark (the ones corresponding to the black ink). Dusting the entire plate with an oppositely charged powder should then make the latent image visible, because the powder would adhere only to the places where charges remained. That powder would form a mirror image of the original page and could then be transferred to a sheet of paper: a copy.

Carlson's knowledge of electrostatics had arisen partly from personal experience. Back in his physics class at Riverside Junior College, a student had asked the teacher one day whether static electricity had any commercial use, and the teacher had said that it did not. "But at that time I was working for a cement plant," Carlson recalled later, "and I could think of one commercial use for it—in separating dust from the flue gases and separating smoke from the air." The plant where Carlson worked had been sued by neighboring orange growers, whose trees became coated with the fine white dust that billowed from the plant's smokestacks. The plant had been able to eliminate the problem and satisfy the growers by installing two sets of electrodes in the flues—one to give escaping dust particles an electrostatic charge and the other, of the opposite polarity, to pull the charged particles out of the air. The copying process that Carlson had now conceived would operate in a similar manner—except that the electrostatic charges he had in mind would be used not simply to attract dust randomly but to form it into a comprehensible pattern.

Few big inventions truly have a single inventor; most technological revolutions are essentially collective efforts, arising in several minds and in several places at more or less the same time, generated as much by cultural pressures as by spontaneous individual insight. If Gutenberg hadn't thought of movable type in the early 1400s, someone else would have, because other advances in printing technology, along with an accelerating increase in the demand for books, had made a breakthrough of some kind inevitable. Carlson, in contrast, was genuinely alone. He always credited Selenyi with having inspired him, but Selenyi never saw the connections that Carlson did. As a matter of fact, in the years following Carlson's discovery, the few people who came up with truly similar ideas were able to do so only after studying Carlson's patent specifications, and their innovations were merely variations on themes he had long since defined. Carlson alone thought of a way to make copies easily and quickly on plain paper; no one yet has come up with a better way of doing it.

"Xerography had practically no foundation in previous scientific work," Dr. Harold E. Clark, a Xerox physicist, told John Brooks in 1967. "Chet put together a rather odd lot of phenomena, each of which was obscure in itself and none of which had previously been related in anyone's thinking." Carlson himself believed that his lonely upbringing had contributed to his success: spending so much time in his own company had given him an acquired immunity to conventional thinking. "The result was the biggest thing in imaging since the coming of photography itself," Clark continued. "Furthermore, he did it entirely without the help of a favorable scientific climate. As you know, there are dozens of instances of simultaneous discovery down through scientific history, but no one came anywhere near being simultaneous with Chet. I'm as amazed by his discovery now as I was when I first heard of it."

Carlson at first called his idea "electron photography," and then he decided upon "electrophotography." As soon as the elements had come together in his mind, the process seemed so intuitively obvious to him that he worried some other researcher would follow the same line of reasoning and beat him to market with a functioning product. He



Pages from Carlson's second (left) and third (opposite page) electrophotography patent applications. Courtesy of the United States Patent Office.

called his old roommate Dumond—who had been fired from his job at the *Daily News* and was now managing a small investment fund for some midwestern businessmen—and asked him to meet him at a local Automat. (Carlson had recently served as the best man at Dumond's wedding and, as a prank, had hidden a wound alarm clock in the newlyweds' honeymoon luggage.) Over coffee, Carlson described the idea behind electron photography and then asked Dumond to sign and date a document stating that Carlson had explained the process to him and that he understood it. Carlson wanted this affidavit as proof of his priority, in the event that someone else should think of a similar idea while he was working on a patent application. Dumond happily complied. Carlson also asked his employer to grant him permission to apply in his own name for a patent for an "improvement in photography"—which, he explained, was unrelated to his work at the company—and Mr. Mallory himself approved his request (in a letter headed "Dear Carlson").

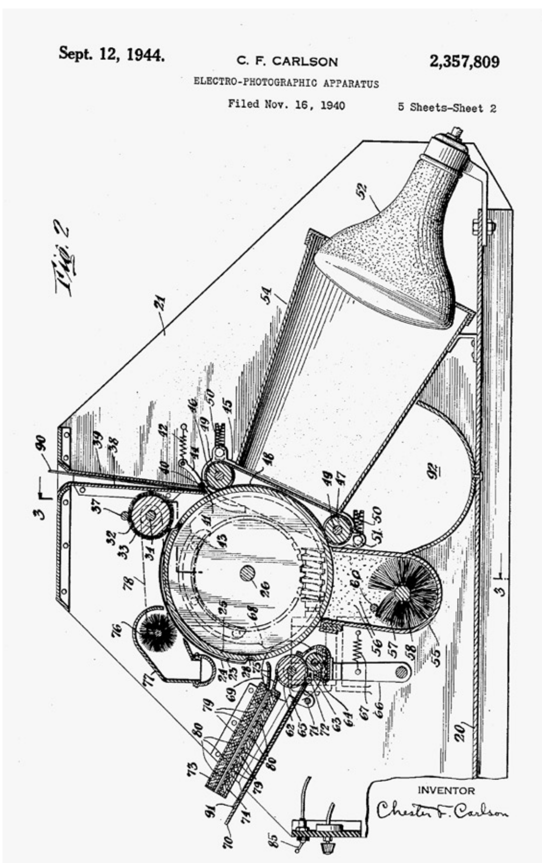
With these documents in hand, Carlson went to work on his patent application, a task for which his job, his legal studies, and his methodical temperament suited him perfectly. He filed his first application in the fall of 1937 and followed it a little over a year later with an improved and expanded version. That expanded patent, which was issued in the fall of 1942, has been regarded ever since as a model in the genre: Carlson knew how to protect an invention. In just a dozen pages and a few simple drawings, he lucidly anticipated and described virtually every aspect of what would ultimately become known as xerography.

Confident that he had now done everything he could to protect himself from competing inventors and manufacturers, Carlson set out to establish that his idea would actually work. In this, he was far less successful. He was positive, he said many years later, that he had truly solved the copying problem, and he was equally confident that his invention would one day be a commercial success. But his efforts to prove the practicality of his idea—to actually make a copy of something—were painfully unproductive. He could see the process in his mind, and he could understand how its elements fit together. But he couldn't make it work.

One of his difficulties was the manual ineptitude that he had noted in his college diary (and which had contributed to his decision to transfer out of his experimental job at Bell Labs). Another was the circumstances under which he was trying to work. Since January 1938, he and Elsa had been living with Elsa's parents in a small house in Jackson Heights. He conducted his experiments in the house's old coal cellar when he could, but there were times when he needed running water and an open flame, and that meant he had to share the kitchen with his wife, who resented the intrusion. He stocked a single shelf with a modest selection of experimental supplies: a jar of chemically pure crystalline sulfur (a photoconductor), which he had bought at a chemical supply house called Eimer & Amend; a few business-card-size zinc engraver's plates; and a miscellaneous collection of parts from which he hoped to fashion an electrostatic generator. He concentrated at first on coating one of the plates with sulfur, by sprinkling crystals on the zinc and using a pair of pliers to hold the plate over one of the burners on the kitchen stove. He found that if he held the plate at the right distance

The usual result of these efforts was not a uniformly coated plate but a sulfur fire, which filled the kitchen with acrid fumes and made the entire building smell like rotten eggs. These accidents annoyed his wife and drew bitter complaints from his mother-in-law. "My experiments became very unpopular around the house," he told an interviewer later.

from the flame and kept it moving, the crystals would eventually liquefy and spread across the plate—although the usual result of these efforts was not a uniformly coated plate but a sulfur fire, which filled the kitchen with acrid fumes and made the entire building smell like rotten eggs. These accidents annoyed his wife and drew bitter complaints from his mother-in-law. "My experiments became very unpopular around the house," he told an interviewer later.



His attempts to make a suitable developing powder were unpopular as well. "I decided that the way to do it was to spray-dry a solution of a dyed resin in a highly volatile solvent in a spray booth or chamber and collect the deposit," he recalled later. "Well, in an apartment I didn't have a very convenient spray chamber, so I decided to use the bathtub. I got an air brush, which is a form of spray gun, and I produced a solution of resin and dye and acetone, and I pulled the shower curtains around the tub, and I sprayed the solution into the space above the tub, and it settled down and I swept it up. Unfortunately, the tub was not very clean after that."

Carlson eventually realized that his apartment made a poor laboratory and that he needed help with his experiments. In the fall of 1938, nearly a year after filing his first patent application, he rented a room on the second floor of a house owned by his in-laws, at 32-05 Thirty-seventh Street in Astoria, Queens. The room had once been the kitchen of an apartment, which was now occupied by a beauty parlor, and there was a bar downstairs. But the room contained a sink and a gas connection, the house was a fifteen-minute walk from home, and the rent (payable to his mother-in-law) was just $15 a month.

Next, he set out to find an assistant. He returned to the library and searched through the classified advertisements in the back pages of scientific magazines. The American economy had been paralyzed for most of a decade, and many scientists were unemployed, but few of them, apparently, saw any point in advertising for work. Carlson could find only one ad that seemed promising. It was in a magazine called *Electronics,* and it had been placed by an Austrian physicist named Otto Kornei, who had recently immigrated to the United States and had had no luck in finding work. Kornei had decided, in desperation, to spend the last of his minimal savings in publicly seeking a job. Carlson's response was the only one he received.

The first xerographic image, now at the Smithsonian. (Courtesy of Xerox Corporation.)

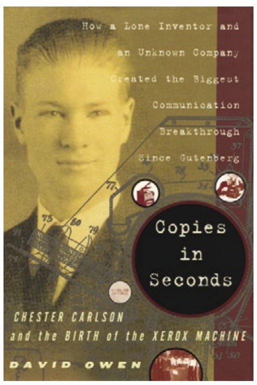
Carlson's own finances in 1938 were far from robust. His final salary at Bell Labs, in 1933, after a companywide wage cut, had been $100 a month. He was making roughly three times that much at Mallory, and he was earning regular raises, but he could not afford extravagances. His budget in 1935 had added up to a little over $230 a month, including $45 for rent, $20 for entertainment for himself and Elsa, and $50 for groceries. Now he was bearing the additional expense of law school. The salary that Carlson offered to Kornei was small in absolute terms—just $90 a month for a period of six months, plus an expense budget of roughly thirty cents a day—but it represented a major portion of his resources. Elsa was already annoyed by his copying obsession; she can't have been pleased that he had now decided to devote more than a third of his gross income to pursuing it.

Kornei was scarcely more enthusiastic. He was a skilled experimental scientist, and he had spent the previous two years, in Vienna, working as an electrical engineer. In a better economy, he would have had his choice of good jobs at big companies. Instead, he found himself being interviewed for a virtually imaginary position by a man who not only wasn't a research scientist but held a mundane job in a corporate back office. The offered salary was low even by the standards of the Depression, and Carlson's so-called laboratory looked more like a janitor's closet—which, in fact, it had once been. Carlson, furthermore, was not a salesman. He was thirty-one years old but looked and acted older, and he dressed like an actuary. He showed Kornei his patent application and gave him a lucid explanation of his idea, but he was too reticent to be able to convey more than a fraction of the excitement he felt about electrophotography, much less to inspire someone else to share it. Carlson augmented the offered salary by promising Kornei 20 percent of the first $10,000 in Carlson's net proceeds from the invention, and 10 percent after that. Kornei agreed to the terms but viewed the offered royalty less as a deal-clinching inducement than as additional evidence that his employer was living a fantasy.

Nevertheless, Kornei turned out to be an ideal assistant. He went to work on October 6, 1938, and in just a few days he made more concrete progress with electrophotography than Carlson himself had managed in more than a year of fumbling experimentation. Coating a zinc plate with a thin, uniform layer of sulfur—a task that had virtually defeated Carlson—turned out to be easy for Kornei. He also showed Carlson that there was no need to build or purchase an electrostatic generator, since they could create a sufficient electrical charge by rubbing the coated plate with a pocket handkerchief or a scrap of fur. And almost immediately he had some limited success in partially discharging coated plates by exposing portions of them to sunlight. That experience persuaded him that he needed a stronger and more reliable light source than the sun shining through the window, and he told Carlson on October 19 that they needed to invest in a Mazda No. 2 Photoflood lamp. Carlson agreed.

The following Saturday, Carlson visited the lab, as he did each weekend. Kornei had already coated a zinc plate with sulfur, and he had ground down the surface with emery paper and polished it with precipitated chalk. He had also purchased a small quantity of lycopodium powder—the extraordinarily fine yellow spores of a plant known as club moss or Christmas tree fern, and the same substance Paul Selenyi had used to develop his facsimile images. (Lycopodium powder is so fine that it is used as a dusting agent in a variety of scientific experiments, and is so water-repellent that it was once sold as baby powder. If you sprinkle lycopodium powder on water, it will float on the surface indefinitely; if you then stick your hand into the water through the film of powder, the lycopodium will coat your hand like a glove and keep your skin dry. It's also explosively flammable and was the key ingredient of early flashbulbs.)

Kornei arranged these materials on a table. "He pulled down the window shade and charged the sulphur surface in the darkened room by rubbing it with a cotton handkerchief," Carlson wrote later. "Then he laid a transparent celluloid ruler having black scale markings on the charged plate and turned on an incandescent lamp (photo flood lamp) for about 10 seconds." The lamp was positioned about a foot above the ruler and the charged plate. "He then turned off the lamp and carefully removed the ruler. Nothing was visible on the plate in the subdued light of the room, but an electrostatic image was there. He sprinkled a little lycopodium powder from a cloth-covered test tube onto the sulphur surface then gently blew away the loose powder. There, adhering to the plate, was a perfect image of the scale of the celluloid ruler, every line and inch number standing out sharply as little ridges of powder."



Carlson raised the shade and held the plate to the light. "The powder image was adhering to the plate by virtue of relatively small, but nevertheless real, electrostatic forces," he wrote. "Kornei then drew his finger over the surface of the plate wiping away the powder image." Kornei took a glass microscope slide and, using India ink, wrote the place and date on it: "10-22-38 ASTORIA." He then closed the shade again, rubbed the sulfur-coated plate with his handkerchief, placed the inscribed slide on the charged surface (as he had previously done with the ruler), turned the flood lamp back on for another ten seconds, and dusted the plate with lycopodium powder. "The letters came out clearly," Carlson wrote, "proving that the plate could be re-used without difficulty."

They repeated the experiment several times, to convince themselves that it worked, then walked to Carlson's apartment and got some waxed paper. Back in the lab, using Kornei's slide once more, they went through the steps again. This time, though, they didn't wipe away the developed image from the surface of the sulfur-coated plate. Instead, Carlson cut out a small rectangle of waxed paper and pressed it against the image, so that most of the lycopodium powder stuck to it. He then placed a warm metal plate against the back of the waxed paper, softening the wax so that the powder became embedded in it. Carlson was now holding the world's first xerographic copy. (You can see it today at the Smithsonian Institution.) He gazed at the paper for a long time, and held it up to the window. Then he took his assistant to lunch.

Carlson felt elated. And, indeed, the sudden appearance of a reproduced image on a photoconductive plate seems almost magical. Charging and exposing a plate makes no change in its appearance, yet if you then sprinkle powder over the surface and blow, an exact facsimile of the original image appears all at once, just as if it had been printed there. In two weeks of experimentation, Kornei had fully justified Carlson's confidence in the process he had conceived. Electrophotography worked, and it worked exactly as he had predicted it would. All that remained to do was to refine the basic process and incorporate it into a functioning office machine. □

This, of course, was not as easy as it sounds—the XeroX 914, the first plain-paper copier for office use, didn't come out until 1960. For the full story of Carlson's rags-to-riches life, and the 20-year struggle to build a commercially viable product after meeting what he called "an enthusiastic lack of interest" from two dozen companies including Eastman Kodak, GE, IBM, and RCA, read the book. Copies in Seconds *is available in bookstores, or it can be ordered directly from the publisher, Simon and Schuster.*

David Owen is a staff writer at The New Yorker.

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