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COURTESY OF MICHELIN NORTH AMERICA

THE COVER: An early test model shows the two essential features of radial tires: Cords that go straight across the tread instead of at an angle, and steel belts for reinforcement. These simple changes caused great upheaval in the American tire and car industries, but today they make automobiles handle better and save billions of gallons of gas a year. To find out how, see page 28.

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PRINTING

How today's computer printers came to eject microscopic dots with amazing precision

IN THE FIRST FEW DECADES OF DIGITAL COMPUTING, THE OUTput of printed information to the user was essentially an afterthought. Typewriter-style impact technology, in which a piece of metal in the shape of a letter was struck against a ribbon, remained virtually universal. The method was simple, well understood, and fast enough for most purposes: When multiple type elements, such as daisy wheels or spinning balls, were spaced along the width of the page, printing speed could be increased to a thousand lines per minute in so-called line printers or page printers. Yet besides being noisy and inflexible (font and size changes were difficult), the impact method suffered from all the limitations and potential for breakdowns associated with mechanical parts. As the type was jerked up, down, and sideways at ever-increasing speeds, great ingenuity was required just to keep it stationary relative to the page at the moment of striking.

Researchers experimented with a number of methods to eliminate the need for moving type. IBM engineers developed a system that magnetized a metal drum in the pat-

The 1984 ThinkJet, Hewlett-Packard's first inkjet printer (seen at top left), printed at 96 dots per inch, leaving a noticeably fuzzy outline.

An IBM Selectric typewriter makes much sharper characters, though the tops are a bit ragged since the type ball did not hit the paper exactly squarely.

An early dot-matrix printer achieves only 80 dots per inch, and the dots are much darker on the "hilltops" of the microscopically rough paper surface.

TOP: COURTESY OF HEWLETT-PACKARD;
BOTTOM ROW: COURTESY OF NIELS NIELSEN

ENTERS THE JET AGE

BY THOMAS KRAEMER

tern that was to be printed. A specially formulated magnetic toner was attracted to the pattern and reproduced it on a sheet of paper, as in a photocopier. Unfortunately, even after the application of pressure and heat, the toner tended to fall off the paper. This and other problems eventually dissuaded IBM from pursuing such a novel technology.

The company also developed a printer that displayed the type on a cathode-ray screen and photographed it. The resulting image could be examined directly on film or reproduced on paper using a standard microfilm printer. This method held some promise, but it had been developed with vacuum tubes, and after IBM switched to transistor-based electronics in 1957, the project was abandoned.

More successfully, a grid of wires or pins could be programmed to strike the page in different combinations for different letters. Since a single set of pins could print any character, this method eliminated the problems associated with sorting through bits of metal type and then moving and stopping them. It also allowed greater flexibility with such things as underlining and italics. Dot-matrix printers, as they came to be called, dominated computer printing from the 1960s into the 1980s and can still be found in many places.

Unfortunately, since dot-matrix was still an impact method, the noise problems and speed limitations of impact remained. Moreover, while characters made of dots were fine for informal use, they looked tacky beside a typed letter or document. When word processing became as important as number crunching, a fast, quiet, high-quality printer loomed as one of the industry's greatest needs.

That need was first met in the early 1980s by the laser printer. This technology, originally developed in Xerox's research laboratories, worked like a photocopier or IBM's magnetic printer, only instead of using regular light or magnetism to create a pattern on a printing drum, it used a laser. By eliminating the need for physical impact against a ribbon, laser printers achieved much higher speeds and were able to work in almost eerie silence.

Most important, they offered unmatchable resolution: 300 dots per inch in early models, or roughly three times what

By making a second pass, Hewlett-Packard's 1985–86 QuietJet could print 192 dots per inch. Drop size would later be reduced for better results.

The 1988 DeskJet printed 300 dots per inch and used a specially formulated ink that allowed smaller drops, which resulted in more precise characters.

By 1995 the DeskJet 800 was up to 600 dots per inch and shot out droplets one-sixth the volume of those used in the ThinkJet of a decade before.

the best dot-matrix printers could achieve. As personal computers grew commonplace during the 1980s, laser printers became the only acceptable choice for "letter-quality" printing, even though a typical model cost several thousand dollars. By 1990 the price had come down to a manageable, though still hefty, $1,000, and today's laser printers go for as little as $200.

Yet the laser printer's dominance was short-lived. The technology that would eventually overtake it was developed at the pioneering electronics firm Hewlett-Packard (HP). Although HP's invention would come to dominate the personal computer market, it was not originally intended for PCs, since in the late 1970s, when the project began, there were no such things. Instead, HP was looking for a new printing mechanism for portable, battery-powered calculators, which were its most lucrative consumer product. Little did HP's management, or anyone else, suspect that its novel printing technology would rise from accessory status to become a stand-alone item that would make a hundred times as much money as calculators ever did.

Hewlett-Packard had been founded in the late 1930s by William Hewlett and David Packard to build electronic instruments and scientific equipment. In 1972 the company branched out with a device that had been a pet project of Bill Hewlett, the HP-35 handheld scientific calculator. Hewlett already owned a large, 30-pound desktop calculator, but he wanted one that could fit in his shirt pocket. (HP Labs engineers actually measured his shirt pocket to determine the size.) Texas Instruments had put a simple four-function calculator on the market in 1971, but HP was the first to squeeze all the major scientific and trigonometric functions into a small 9-ounce package.

One of the company's main goals in its printer project was to reduce the power consumption of its printing calculators. At the time, some calculators output their results by striking a type bar (which would generally have a smaller character set than computer printers, containing just the 10 digits and a few other characters) against an inked ribbon. Others had thermal print heads, consisting of a small column of resistors that could be electrically heated and pressed against a thermally sensitive paper or ribbon. Thermal printers, which were both integrated into hand-held calculators and sold as separate units, required a special kind of paper and had problems with the type fading over time. They also used a lot of battery power. That was a major consideration, especially when liquid-crystal calculator displays replaced power-hungry light-emitting diodes and printers became the biggest drain on batteries.

The inkjet-printer project grew out of Hewlett-Packard's effort in the 1970s to reduce power consumption in its printing calculators.

Printer research had been a part of HP's calculator development work since the beginning. In the early 1970s, the engineers at HP's advanced research laboratory in Palo Alto, California, who designed the HP-35 also built a prototype "pocket plotter" to output graphs. This was a small device that had a flexible tongue with a felt-tip pen at the end. The tongue could be rolled in and out like a metal tape measure to draw lines in one direction. The device also grabbed one edge of the paper and could roll it back and forth, allowing anything to be drawn on a sheet of paper many times larger than the pocket-sized plotter.

HP engineers in San Diego and in Andover, Massachusetts, developed this prototype into a practical device they called a "grit wheel" plotter, which was used with computers and graphing instruments. Their breakthrough design became the standard for all X-Y pen plotters (as such devices were known) in the 1980s. In

The X-Y plotter, an ancestor of the inkjet printer, used a grit wheel to move the paper along one axis while a felt-tip pen was driven back and forth along the other.

FROM *Hewlett-Packard Journal*, DEC. 1982 these plotters, small grit wheels (rollers faced with rough, sandpaperlike material) grip the edges of a piece of paper and move it underneath a bar holding a felt-tip pen that can run back and forth. Before grit wheels, X-Y plotters had been built with a pen mounted on two large arms, one of which would move the pen in the X direction and the other in the Y direction. The grit-wheel design eliminated one of the plotter arms by moving the paper instead. This change allowed faster drawing speeds, because paper can be moved more quickly than a mechanical arm.

William Hewlett and David Packard, founders of the company that bears their names, inspect a transistorized electronic counter at a company factory in 1963.

Building on this success, in 1978 managers of HP's Corvallis, Oregon, facility, which specialized in calculator design, started a project to apply the grit-wheel idea to calculator plotters. (As calculators had gotten fancier, they had become capable of generating graphs, but the old thermal printers could do no better than a series of dots, which usually gave a less than satisfactory rendering.) Midway through the project, however, HP management decided to transfer engineering responsibility to the San Diego division, which had developed the company's previous plotters. The decision freed several Corvallis engineers for reassignment, including Niels Nielsen, who would go on to become a pioneer in inkjet printing technology.

The inkjet project began in the fall of 1979, when Corvallis's engineering manager, Ernst Erni, was promoted to direct the engineering of integrated circuits (ICs), liquid-crystal displays (LCDs), and thermal print heads for calculators. Erni later explained, "We needed more products to fill up our manufacturing capacity. You have to run your fab [i.e., fabrication] at full capacity to maintain quality and make a profit." As part of his reorganization plan, Erni asked a member of his management staff, Frank Cloutier, to investigate improvements in print heads and displays.

Cloutier traveled to HP's central advanced-research laboratory in Palo Alto to look for new ideas. While he was there, an engineer named John Vaught demonstrated his idea of using thermal heating to eject droplets of ink through a tiny orifice to print text. The idea of inkjet printing was not new in itself; it had been used as early as 1950 in instrument recorders and other specialized applications. Later it was adopted for jobs like the high-speed printing of custom date codes and magazine labels. But Vaught's mechanism was the first one Cloutier had seen that looked suitable for use in a mass-produced consumer product. Cloutier recalled, "By making a pen low enough in cost, I realized that you could make it disposable. Our decision to make it disposable turned out to be essential, since we were unable to build an inkjet pen reliable enough to last longer than one fill of ink." Cloutier took Vaught's idea back to Corvallis and began to develop it into a working prototype.

Some important design goals were set early on. Cloutier told his staff: "Printers are very noisy, and we want to build a quiet one. Calculator thermal printers require a special heat-sensitive paper, and we want to be able to print on ordinary office typewriter paper. We don't want the customers to get ink on their hands when they change pens. And, of course, we need a low power consumption rate so that we can run on calculator batteries."

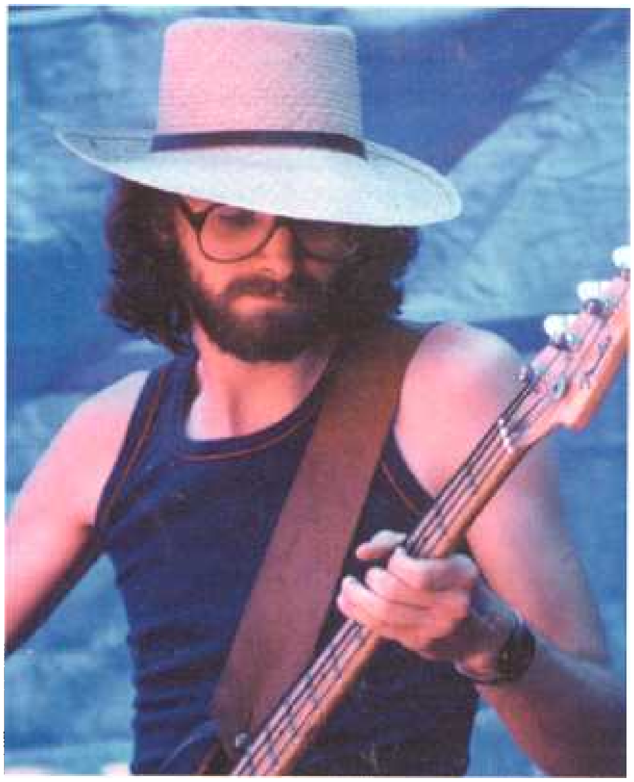
The inkjet project got a big boost when its research staff acquired the services of Niels Nielsen, a very free-spirited mechanical engineer with less than a year's experience. Nielsen became famous within HP for wearing a different hat every day. For several years, he drove to work in an old Cadillac hearse. You could usually find his desk decorated with a pink plastic lawn flamingo, a war-surplus bombshell beside it.

Nielsen began by assessing the existing technologies. "We looked at the inkjet printers used in industrial applications and found them to be expensive because of the pumps and hoses they needed to spray ink out," he later said. A key goal for HP would be finding a simpler way to expel the

JON BRENNEIS/TIMEPIX

ink. "In 1979," Nielsen continued, "Siemens introduced the Pt80i printer that used a piezoelectric device to spit the ink out. This solved many of the problems, but the print head was expensive to produce and we wanted a disposable head for reliability."

As Nielsen said, the Siemens inkjet printer relied on piezoelectricity, which is the tendency of certain crystals to generate a mechanical stress when subjected to an electric current (or alternatively to generate an electric current when subjected to a mechanical stress). In the Siemens printer, an electric current was applied to piezoelectric crystals, causing them to exert a force on the ink in a tube and eject it through a hole onto the paper. While clever and reliable, this method was not suited for a low-cost, disposable item. Vaught's idea of using thermal heating, however, looked promising for mass production. In the spring of 1981 the inkjet project was officially named St. Helens, after the nearby volcano, whose eruption reminded engineers of the expulsion of ink from a heated orifice.



Niels Nielsen, who was a noted free spirit, interrupts his inkjet work to rock the joint at a company picnic around 1980.

The first one-dot prototype that Vaught had shown Cloutier at HP Labs consisted of a plate with a groove in it and a thin-film resistor aligned over the groove to form a tube. Ink was fed into one end of the tube, and when the resistor heated up, the ink would boil and spit out the other end. Cloutier recalled, "I realized how difficult this would be to manufacture, since cutting a precision groove and carefully aligning a resistor over the top of it would involve a lot of labor. I then thought of how integrated circuits are manufactured, by building many of them on a single wafer and cutting them apart when they are done. If we built a large sheet of print heads at one time, the cost of labor to align the orifice hole over the resistors would be less.

"I took a piece of thin brass shim stock, punched the tiniest hole I could with a sewing needle, put it over a resistor covered in ink, and then looked at it under a strobe microscope." Cloutier applied repetitive pulses of current through the resistor, and "It worked! After a while I couldn't see anything anymore. I stepped back and saw I was completely covered in black ink. So a suit of clothes and several tries later, we had the architecture that we still use today." Cloutier saved his ink-stained tie, and he often displays it at company functions. Lab coats and black jeans quickly became the clothing of choice for inkjet engineers.

The shim-stock print head could shoot regular fountain pen ink several inches through the air. Cloutier and his team quickly discovered, however, that surface tension and capillary forces were not enough to keep the ink from drooling out of the nozzle. If the "pen" (as the combination of the print head, ink reservoir, and plastic body was known) was dropped, ink would come gushing out. Engineers tried antiwetting coatings on the outside of the hole to prevent the puddling of ink on the print head's surface, but they were not durable enough.

Because of a lack of space, a broom closet became a makeshift laboratory. Dave Lowe, an early team member, described one of the project's first triumphs: "Niels was always in the broom closet in his lab coat drenched in magenta ink, with the prototype pen sitting under the microscope spitting ink. One day we decided to go for it and print. The pen was hooked up to a computer, and I had already loaded some basic fonts. Niels moved the paper over the print head while I ran my program to drive the pen. Ernst had promised us hamburgers when we got our first words printed." A line of recognizable characters emerged, and they got their hamburgers.

Enthusiasm over the success of the early prototypes led the calculator division to expand from printhead development to a full-fledged printer project. Since the pen's design was just starting to take shape, the printer designers drew an imaginary box of a size that fitted their needs and gave this as a constraint to the pen designers. The entire print head, ink and all, could take up no more than one cubic inch. As the project progressed, this combination of a fixed size and a fast-track approach made it hard to solve many of the pen's design problems. It also limited how much ink could be stored in the print head. Because the printer's ports were being developed simultaneously, an early prototype print head had to be mounted in a modified HP 82905A dot-matrix printer built for HP by Epson.

To eliminate the drooling and space problems, Lowe thought of holding the ink in a small rubber thimble. Not

BOTH PAGES: COURTESY OF HEWLETT-PACKARD

only was this very space-efficient, but the eyedropper action created the needed back pressure to keep the ink from drooling out. It also helped prevent the ink from drying out through the plastic pen body.

The size, number, and spacing of the holes was another matter that required considerable experimentation. According to Nielsen, "We decided to make the inkjet head 12 dots high, because we could do it technically and be competitive with dot-matrix printers that printed 9-dot-high characters." The vertical spacing between the dots was limited by the design requirement that the printer have 96-dots-per-inch resolution. Staggering the holes in two columns would have allowed tighter spacing, but low-cost printer mechanisms could not move the pen accurately enough to correctly align a second column of dots with the first. Later generations of printers used a specially designed motor controller circuit to accommodate staggered columns of holes.

Nielsen and his co-worker Kevin Hudson experimentally determined that a six-microsecond electrical pulse was optimal to boil the ink and expel it out the orifice hole. The final design constraints required the ink-drop size to be 200 picoliters, which yielded a dot about .012 to .015 inch in diameter. Nielsen calculated that with the average text character requiring 17 dots, 750,000 characters could be printed with the volume of ink contained in the space he had been allowed by the printer designers.

The printer designers drew an imaginary box for the pen designers. The entire print head, ink and all, was allowed one cubic inch.

Having demonstrated the feasibility of the basic principle, the team next had to show that an inkjet print head could be mass-produced at a reasonable price. Paul McClelland said, "In my previous job at Tektronix I had seen electroforming used to make very small parts. We used it to create the precision ink nozzle holes in the orifice plate. It sure beat using a sewing needle." Electroforming is a process similar to the one used for plating chrome onto a car's bumper. A mandrel—a thin form made of stainless steel—is carefully fabricated in the shape of the final part. A thin layer of metal is then plated electrochemically onto the mandrel's surface. When finished, the metal part is popped off the mandrel, which can be used again to make another part. Precision holes and shapes can easily be formed in a thin piece of metal by shaping the mandrel appropriately. Electric-shaver heads and metal coffee filters are among the products manufactured with electroforming.

Cloutier's idea of building a large number of components at one time and then cutting them apart was another valuable insight. The 12 miniature resistors that were needed to boil the ink out of the precision nozzle were fabricated on a glass plate, using a process similar to the technology that produced electronic IC chips. Unlike standard IC resistors, these resistors needed to be strong enough to withstand the forces of boiling ink bubbles, for when the resistors burn out, the print head quits working. This constraint required careful selection of size, shape, and material.

The print head for the 1984 ThinkJet was disposable and easy to replace, which was important for a product aimed at the business and consumer markets.

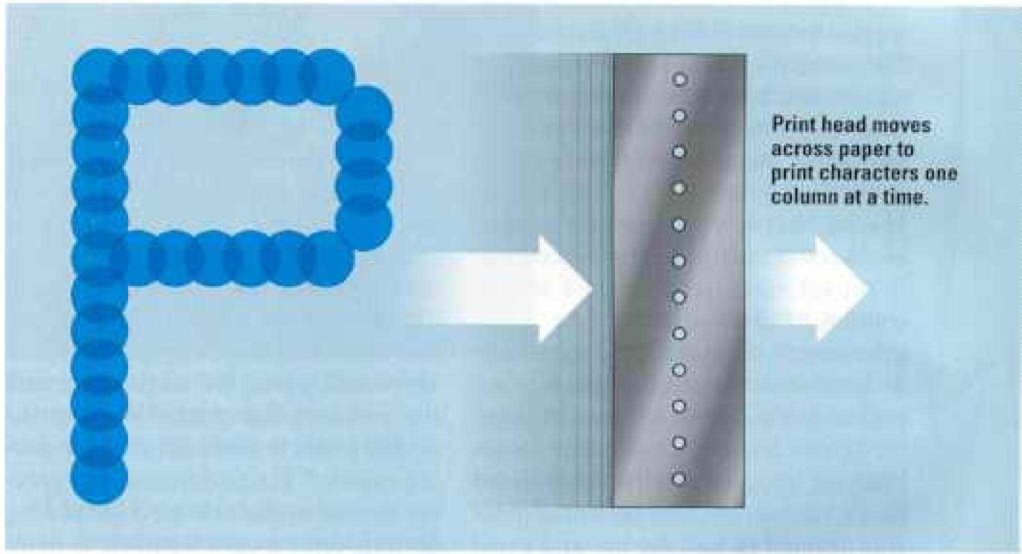
One very active area of research was the development of the adhesive used to attach the print head to the ink-reservoir cartridge. Nielsen said, "For our glue we went to the lab stock cabinet and found household RTV silicone," an adhesive sealant that is commonly used to caulk bathtub tile. It would be nice to report that this chance discovery yielded the perfect adhesive, but in fact the RTV silicone was attacked by the ink and proved difficult to use in manufacturing: It was hard to apply in an even bead on each part, and it exudes a variety of contaminant oils that destroy the inner workings of the print head. After consulting 25 glue manufacturers, the fabrication team chose an adhesive that could be cured by ultraviolet light. Besides resisting the ink better, this simplified the manufacturing process by reducing the curing time and eliminating variations in bond strength between parts.

Another problem the designers had to deal with was the tendency of the inkjet nozzles to get clogged with paper lint and dried ink. Today's inkjet printers include a "service station," which periodically wipes the head and spits ink into a small spittoon to clear the nozzles. These service stations also cap the pen when it is not in use, to keep the ink in the nozzles from drying out and clogging. In the initial version, however, with the printer mechanism's design fixed in advance, there was no space to add a service station. As a result, early inkjet users often resorted to paper clips and tissue paper to force ink out of the print head. Cloutier's goal of keeping the user's hands free from ink was not achieved by the first product.

The inkjet method required an ink that would dry on paper quickly but not clog or corrode the nozzles. Company chemists eventually settled on a nontoxic water-glycol mix commonly used in fountain pens. This formulation reduced clogging and avoided the problem of ink mist, a spreading of the dots that makes characters look like graffiti written with spray paint.

Though the chosen ink dried quickly by absorbing into the paper, it was not waterproof. This meant that it would smear if a drop of coffee was spilled on the page or a highlighter pen was run across it. Furthermore, the dyes used in the ink were not lightfast, so printed pages would fade when exposed to bright light. It was certainly an improvement from the old thermal paper printers, but it still left much to be desired.

One of Cloutier's design goals had been the ability to print on plain paper. When one early model was fired up, Nielsen could be seen giggling with delight as he used business cards, brown paper bags, and toilet paper to demonstrate that he could print on anything. Yet despite these successes, he recalled, "We quickly discovered that so-called plain office typewriter paper had a lot of variation in how the ink drop would absorb and spread out. Different papers from different manufacturers, even papers from different lots within a manufacturer, would cause the printed dots to vary significantly in size. Because of this, we were unable to guarantee consis-

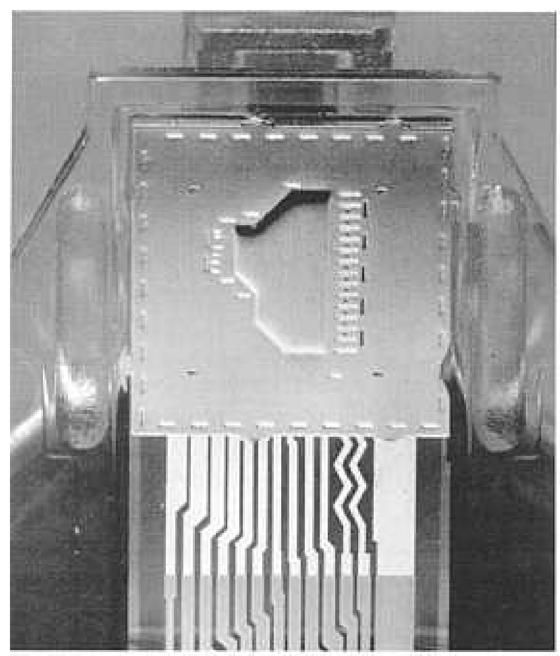


tent print quality without specifying a specially made plain paper."

Inkjet printing still doesn't work well on many papers. The thousands of individual dots have to be consistently absorbed into the paper and have to spread out to equal sizes. These properties obviously depend on the paper's composition and surface texture. Also, some papers curl and wrinkle as the liquid ink dries out.

Paper manufacturing is a proprietary art. Paper can vary depending on where the logs came from and many other processing factors. Before computer printers existed, most paper had been formulated to work with typewriters and office copy machines, which have different requirements. The plain-paper printing problem wasn't really solved until the 1990s, when inkjet printing became so common that the world's major paper companies worked with HP to make all "plain office paper" compatible with both inkjet and laser printers. You can still find some office paper sold internationally that doesn't work well with an inkjet printer, but it isn't easy.

With these and other solutions and work-arounds in place, things appeared to be going well until large-scale product testing began. The first problem to show up was caused by what came to be known as kogation. As Nielsen explained, "We called it kogation after the Japanese word *koga*, meaning 'bis-



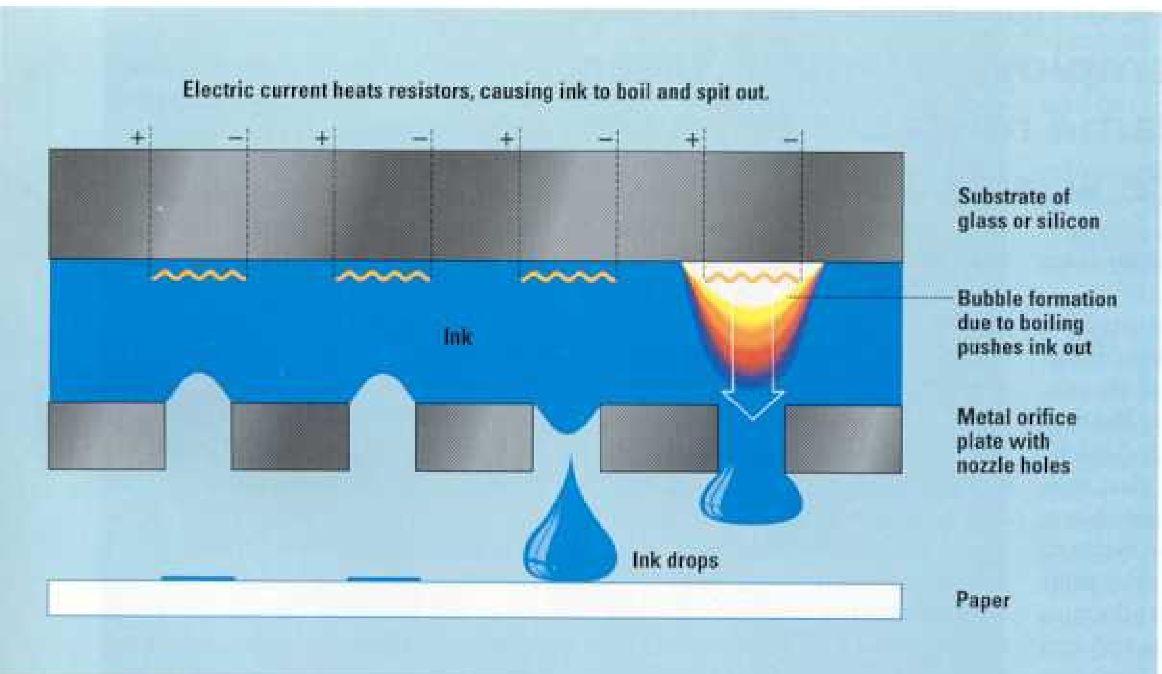
An early print head has twelve tiny holes in a column just right of center. The five vertical slots to their right help keep ink from spilling out the holes next to the proper one during ejection.

BOTTOM: FROM *Hewlett-Packard Journal*, MAY 1985 cuit.' A cruddy residue was observed baking onto the resistor surface in the shape of a biscuit. It looked just like the baked-on residue in a cake pan. It was caused by the dyestuff in the ink chemically reacting with the hot resistor surface to form an insoluble scale that built up with use."

Dave Hackleman, who worked on that problem, said: "Initially, it was expected that some commercially available ink would be acceptable. After some testing, however, we determined that we would have to develop our own ink. Kogation was one of the many problems we had to solve with the ink formulation." The exact ink formula and process is a closely guarded trade secret, just like the formula for Coca-Cola.

A second problem became known just as production was ramping up: When a dot was printing, ink from an adjacent nozzle would incorrectly spit out at the same time. Cloutier said, "This was a killer problem, and it meant the difference between being able to ship our product on time or not. I started a flurry of around-the-clock activity to find a solution."

After reviewing the project's history from design to factory floor, Cloutier discovered that a production change had resulted in what is called hydraulic crosstalk. In this phenomenon, the force of the fluid moving through one nozzle causes fluid in the adjacent nozzle to spit out. Cloutier reached deep into his technical training to find a solution. "While in a panic, I thought up an idea based on an electrical-circuit analogy. The most obvious approach was to place the fluidic equivalent of an inductor [something like a long, thin ink-feed tube leading to each nozzle] in series with the fluid flow path to prevent flow in one nozzle from affecting the other nozzle. I rejected this idea since it would have required a major redesign and delayed the project." However, Cloutier realized that "the fluidic equivalent of a capacitor could be placed in parallel across the nozzles by adding a narrow slot in the orifice plate. The slot formed a fluid meniscus buffer that prevented the hydraulic crosstalk. The slot was easily made with the same electroforming process used to make the orifice plates." With this change in place, ink would bulge out in the slot instead of creating pressure on adjacent nozzles.



Above: Precisely controlled bubbles force drops of ink through the holes. Opposite, top: How characters are formed from dots.

All the design problems were eventually solved, and soon the assembly lines were producing 100,000 print heads per month. Yet the printer's debut was not auspicious. When the HP 2225 ThinkJet printer was introduced, in April 1984, it was barely competitive with dot-matrix printers. (The name ThinkJet came from THermal INK JETting out of a nozzle.) Its main advantages over a dot-matrix printer were that it printed quietly and could run on calculator batteries. Most calculators were connected to the ThinkJet printer via a small wire cable. The stand-alone printer required its own set of rechargeable batteries.

Since this printer had been designed with calculators in mind, it used a standard calculator interface, HP-IL, to specify the form in which information would be transmitted. However, a mid-project design change allowed for a separate version of the printer with a Centronics interface, which became the standard for PC printers. Tom Braun, who worked on the printer design team, said, "We risked slipping behind the project schedule when we decided to provide interfaces other than the calculator one. We tried to minimize this risk by putting the printer interface on a separate plug-in board. We built separate printer models for each interface to keep the cost down. The significance of our decision to have an IBM-compatible Parallel Printer interface was not fully appreciated until after we shipped. PC sales ended up creating a new market for inkjet printers that was many times bigger than calculators ever were." The team also added an Epson printer compatibility mode, so that any software that could print to an Epson dot-matrix printer could also print to the new inkjet printer.

Over the next few years, derivative versions of the first inkjet printer were

ABOVE AND OPPOSITE PAGE, TOP: STEVEN STANKIEWICZ introduced for PCs and minicomputers. Dot-matrix printers, however, continued to dominate because of their low price, while laser printers (including HP's LaserJet line) captured most of the letter-quality market. The first major breakthrough for inkjet came in 1987, when HP introduced full-color inkjet printing with its PaintJet. This product, designed by the company's San Diego plotter division, was intended as an improvement on HP's lower-cost X-Y plotters, which were commonly used to create business graphics and engineering drawings. The PaintJet had two separate pens. One printed black ink only, while the other contained three sets of nozzles for the three primary colors.

The inkjet pen that was created for the PaintJet replaced the rubber thimble with a foam pad that held the ink, as in a felt-tip pen. This was the first inkjet pen to be built on standard IC silicon wafers instead of the glass substrate used by the St. Helens pen. Much later products used the silicon wafer to build transistors directly on the print head, using standard IC production equipment. These transistors reduced the number of electrical connections to the printer, improving reliability and allowing for more printing nozzles on the head.

Inkjet printer sales did not take off until the HP DeskJet printer was introduced in 1988 for just more than $1,000. At last inkjet had a clear price advantage over laser printers, which still cost around $1,500. Today, color inkjet printers are less expensive than black-and-white laser printers. Still, for high-volume black-and-white printing, laser printers costs less per page for supplies, since many toner cartridges cost only two to three times as much as an inkjet pen but can print ten times as many pages.

Several years after the DeskJet was introduced, its black ink was redesigned to be more water-resistant and lightfast. The foam reservoir was eliminated to give more ink capacity, and a fancy regulator was designed to maintain fluid pressures under all operating conditions without letting ink drool out. In 1991 a pen cartridge containing all three primary colors, as in the PaintJet, was designed to replace the black-only pen in the HP 500C printer. Throughout the 1990s, inkjet technology was extended to work in fax machines, copiers, and even commercial applications like automatic teller machines. Photographic-quality prints were obtained with six-color printing and smaller drop sizes, combined with specially coated paper media.

Nielsen complained that newly hired employees would "often repeat the same mistakes since the procedure wasn't documented."

As reliability improved, HP was finally able in 1998 to introduce a print head that could be refilled with ink. This greatly lowered the per-page cost of high-volume printing applications. Disposable print heads continue to be the preferred configuration in lower-cost inkjet printers. You can refill most inkjet pens at your own risk; they just may not work the second time.

Meanwhile, competitors started building inkjet printers of their own. As Epson's dot-matrix sales tapered off, the company developed piezoelectric inkjet printers. Canon independently developed inkjet technology at the same time as HP, and the two companies cross-licensed many patents. Lexmark, IBM's typewriter spinoff, replaced declining typewriter sales with its own inkjet printers. The inkjet business has followed the classic business-school model of giving away the razors to sell the blades. Although HP has never given away printers, some competitors have aggressively priced their printers to gain market share with the expectation of future profits from selling replacement pens. In the face of this tough competition, HP still has the largest market share and has built more than half of all printers in use today worldwide.

In the history of technology, the excitement of the invention phase often overshadows the painstaking development of the production technology needed to make an invention widely available. HP's first inkjet manufacturing area consisted of fewer than 100 people. Just 10 years later, more than 10,000 employees were producing inkjet printers and cartridges, representing billions of dollars in revenue.

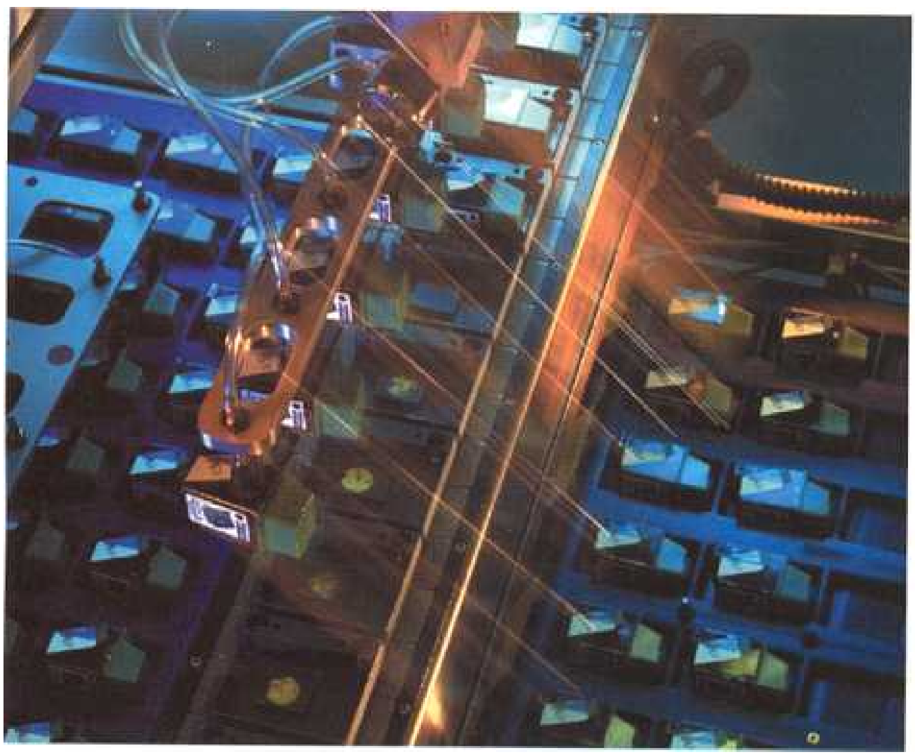
Because of this rapid and unplanned growth, much of the manufacturing operation was developed using "seat of the pants" and "back of the envelope" engineering approaches. Just producing enough to meet consumer demand ended up being a higher priority than cost or quality. Except for isolated attempts at process control by a handful of individuals, the HP inkjet organization developed a culture that thumbed its nose at the rest of HP, which had long since adopted Japanese-style process-control and quality-management systems. With huge customer demand, profits, and growth, it was easy to justify this approach. However, the organization eventually suffered the consequences.

During the late 1980s and early 1990s, quality problems started to show up. Nielsen complained, "I am often called upon to help just like the smokejumpers that parachute in to put out forest fires! . . . Many of the problems occurred because we did not have the time to fully characterize and document everything. Each time a new employee comes on board, they often repeat the same mistakes since the procedure wasn't documented. Also, since we haven't fully characterized the design, nobody understands what knobs to turn to fix problems." Nielsen recently added: "This was made worse by our inability to quickly and accurately trace the flow of raw materials through our factories, and by interdepartmental fragmentation and the lack of a common computer production control system spanning all parts of the factory—all, in turn, caused by our extremely rapid growth."

At long last, the inkjet business-unit manager stopped waiting for a consensus to develop and ordered the implementation of modern process control across the manufacturing division. Implementing this order was complicated, because HP had manufacturing sites distributed around the world, producing billions of inkjet pens each year. Nielsen said, "The variation in our manufacturing process causes each of our pens to work differently. But every pen we make has to work in every printer we previously built and shipped to a customer. This is easier said than done." He adds, "Implementing process control was painful and time-consuming, but the overwhelming complexity of the products we are now mass-producing in 2000 have made computer production control, part tracking, and process control all absolute necessities."

Despite these problems, it is not entirely clear whether modern manufacturing process and quality control should or could have been implemented any sooner. Most new technologies ride the "bleeding edge" and are successful because of engineers' ability to adapt quickly and change course as new things are learned. "Cowboy-style" engineering is rewarded because you can move faster than an engineer who is bogged down in documenting and overperfecting his creation.

Nielsen said, "Inkjet engineers often get rewarded for heroically fixing problems after they happen instead of avoiding them. The engineer who plans ahead and flies around the thundercloud is not a hero like the pilot who flies directly into it and saves the plane from crashing." Amid the continuing tradeoff between moving quickly and documenting your work, there is always a critical point in time when a technology matures and the marketplace demands high quality at a reasonable price. Companies that miss this shift in demand suffer greatly, as American auto manufacturers did in the 1970s when high-quality Japanese cars came on the market.



Inkjet cartridges are fabricated in 1993, when Hewlett-Packard's manufacturing and process engineering were catching up to research and development advances.

When HP moved its calculator business to Corvallis, in 1975, the town leaders saw it as the new "clean industry" that they needed, to make up for the loss of logging and cannery jobs. Things did not always run smoothly at first. Some time earlier, a defunct cannery had been converted into a shopping center called the Old Cannery, and during a few lean years in the calculator business, workers joked that if HP went out of business, their building could be converted to a shopping center called the Old Calculator Factory. Twenty years later the calculator factory was, in fact, moved elsewhere—not because of a lack of sales but to make space for the growth of the inkjet business, which had become several orders of magnitude bigger than the calculator business.

So the need for a calculator printer led to the development of inkjet printers, which then became far more widely used with computers. Today, inkjet technology continues to inspire new product ideas. HP Labs' Barry Willis has discussed the possibility of using inkjet to address the potentially huge market for precise DNA analysis, to enable drug dosages to be based on a person's genetic makeup. Inkjet-based scanners could test thousands of DNA segments for a variety of mutations at a fraction of the time and cost required by current gene-array scanners. Instead of depositing dots of ink on a page, the technology would be used to spray liquefied DNA samples into thousands of miniature "test tubes" for chemical analysis. If this idea, or some other entirely new variation on today's inkjet technology, takes hold and displaces the current manufacturing priorities, perhaps 20 years from now the HP Corvallis site will be called the Old Inkjet Factory. ★

Thomas Kraemer is a former Hewlett-Packard engineering manager who has witnessed the development of inkjet technology over the last 25 years.

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