Robert Garner and Frederick (Rick) Dill

The Legendary IBM 1401 Data Processing System

The development of the most popular computer of the 1960s and the story of its restoration at age 50.

The IBM 1401 Data Processing System was the world's most popular computer during much of the 1960s. Announced in 1959, it was one of IBM's earliest transistorized computers. The IBM 1401 transitioned thousands of businesses and institutions to stored-program computing, and its tape- and disk-oriented systems freed users from the decades-long practice of storing data on punched cards. In 1965, half of all computers were IBM 1401s or members of its family. Figure 1 shows a tape-oriented 1401 system from the 1960s.

In this overview of the development of the IBM 1401 and its underlying technologies, we begin with its vacuum tube forebears. We cover IBM's development of the 1401's basic enabling technologies and trace its origins in business accounting machines. We highlight its key features and characteristics, its market succession, and even its appearance in popular culture. We also describe the volunteer project at the Computer History Museum in Mountain View, California, that successfully restored two tape-oriented 1401 systems to full operation.

Digital Object Identifier 10.1109/MSSC.2009.935295

Early Accounting Machines, Calculators, and Stored-Program Computers

For the first six decades of the 20th century, many businesses processed data for inventory, billing, receivables, and payroll by repetitively passing decks of cards with holes punched in them through various electromechanical "unit record" machines. These machines sorted and merged cards, did simple calculations, punched cards, and printed reports. Most machines were controlled by hand-wired plugboards tailored for particular jobs. By the 1950s, IBM's operations from the leasing of unit record machines and the sale of billions of punched cards each year were very profitable.

By this time, calculators with punched cards for input and output were being used to augment accounting machines. Announced in 1948, the IBM 604 Electronic Calculating Punch was about the size of two refrigerators. It was a vacuum tube, plugboard-controlled, serial-decimal-digit machine with 50 digits of

 1943-0582/10/$26.00©2010IEEE

FIGURE 1: A tape-oriented IBM 1401 Data Processing System from the early 1960s. From left to right: 1402 Card Read Punch, 729 Magnetic Tape Unit, 1407 Console Inquiry Station, 1401 Processing Unit, 1403 Printer. (Image courtesy of IBM Archives.)

storage that could multiply and divide. In 1949, IBM also offered the Card-Programmed Calculator (CPC), a product that interconnected an IBM 604 wired for common subroutines, an extra storage unit, and the popular IBM 402 Accounting Machine [1]. About 4,500 IBM 604s and 130 CPCs were installed [2].

In 1951, UNIVAC pioneered the business stored-program computer. Soon thereafter, IBM and other computer manufacturers introduced computers for the business and scientific marketplaces. The IBM 650 Magnetic Drum Data Processing Machine announced in 1953 was the first widely popular, low-cost business and scientific computer. The 650 was installed at more than a thousand customer sites and rented for about US$4,000 per month (US$32,000 in today's currency) [2]. It was a stored-program computer with instructions and data residing in 2,000 words on a magnetic drum rotating at 12,500 r/min. By 1956, a dozen commercial firms had delivered about 1,000 stored-program computers and 3,200 calculators, with IBM and the Univac division of Sperry Rand leading the marketplace [2].

Broadly speaking, stored-program computers were considerably more flexible and adaptable than plugboard-based accounting machines. Their software was easier to load, maintain, and distribute than wiring and handling plugboards. However, large-scale stored-program computers were too expensive for all but the largest corporations. Typical monthly rentals ranged from US$25,000 to US$40,000 per month (about US$180,000 to US$300,000 today), versus only US$2,000 to US$2,500 per month for a set of unit record machines, such as a 604 Calculating Punch (US$650 per month), a 407 Accounting Machine (US$1,000 per month), a sorter, a collator, and so on [2], [3].

Particularly during the 1950s, computer design was closely interwoven with rapidly evolving circuit technologies and techniques. The 1950s vacuum tube computers—about 3,600 were installed commercially [2]—were typically based on diode logic circuits with vacuum tube restoration of logic levels. Stored-program memories employed mercury electroacoustic delay lines (UNIVAC I), electrostatic Williams cathode-ray tubes (IBM 701 and 702), or other approaches. Vacuum tubes suffered from high heat dissipation and filament burnout from thermal cycling, parameter drift, secondary emission, and dust-induced cathode-to-grid shorts. Storage CRTs suffered from internal particle contamination and proved difficult to manufacture. Vacuum tube machines of this era were typically serviced several times per week. IBM went so far as to establish a small in-house pilot line to demonstrate reliable production of vacuum tubes for computing machines [1]. For main memory, concerted efforts by IBM, MIT, and others made magnetic core the technology of choice due to its high reliability and fast access times. By 1956, IBM had automated the production of its core memory planes [4].

Businesses and institutions throughout the world used the IBM 1401 in the 1960s to process rapidly growing amounts of information.

Early IBM Transistor Development and Manufacturing

Bell Labs invented the transistor in 1947 and broadly disclosed the technology in the summer of 1951. It continued to focus on the point-contact germanium transistor, as did IBM's initial transistor investigations. Although no one knew how to manufacture point-contact transistors reliably with repeatable stable characteristics and reasonable gain, their faster speed over junction transistors was attractive to computer designers [1]. Also, due to a negative resistance region at higher emitter currents, a bistable latch could be implemented with just a single point-contact transistor instead of a cross-coupled pair of transistors [5].

In 1952, Joseph Logue joined IBM's nascent transistor research group in Poughkeepsie, New York, after troubleshooting IBM 701 storage tubes. He concluded that alloy-junction transistors were far superior to point-contact devices for digital logic circuits because of their higher current gain, greater fan-out, and orders-of-magnitude lower collector cutoff current. Even though alloy-junction was slower and more temperature-sensitive than point-contact, he advocated for alloy-junction's higher reliability and predictability, lower manufacturing cost, and greater circuit versatility [6].

In 1953, Logue conducted a class in transistor digital circuit design. For lab assignments, six IBM vacuum tube machines were reconfigured to use transistors. One of the projects was a cross section of the IBM 604 calculator. The design project subsequently grew into a working prototype of a fully transistorized 604, publicly revealed in October 1954 and demonstrated in several U.S. cities [1], [6]. Based on this effort, IBM's 608 Transistor Calculator product was announced in April 1955, and it became the world's first fully transistorized commercial calculator when delivered in December 1957 [1]. Nevertheless, only 32 units were produced, as it became outmoded by other IBM products [4], [11]. Figure 2 shows a photo of a transistorized 604 printed-circuit card.

FIGURE 2: **A printed-circuit logic card with germanium diodes and alloy-junction transistors from the 1955 experimental transistorized 604 calculator—basis of the IBM 608, world's first fully transistorized commercial calculator. (Photograph courtesy of Robert Garner.)**

In place of the IBM 604's 1,400 twin-triode tubes, the transistorized version used 2,200 alloy-junction germanium transistors; it occupied half the volume and consumed 95% less power than the original. Even its power supplies and neon tube indicator drivers were solid-state, the first time all functions of a large electronic calculating machine were implemented with transistors [1]. Its direct-coupled transistor and diode-transistor logic ran at a 50-kHz cycle rate with 5-V signal swings [7]. To access its magnetic core memory, three parallel transistors were needed to drive a core half-select line [4].

Although the transistorized 604 was very reliable, one issue with early alloy-junction transistors was that base resistance was too high for digital circuits. Logue attempted to convince transistor vendors—GE, Raytheon, RCA, and Westinghouse—to lower base resistance, but the effort was to no avail since their transistors met the needs of the more popular communication applications.

In 1954, a Poughkeepsie research team (working in the site's defunct pickle factory) began to design transistors for use in future calculators and computers. To lower the transistor's base resistance, they used a disk-shaped base with a ring contact around its circular periphery. The emitter was alloyed on one side of the disk and a larger collector on the other, allowing for some misalignment (see Figure 3).

In 1956, anticipating the need to lower the manufacturing costs of its upcoming transistorized computers, IBM established a small group in Poughkeepsie responsible for mass-producing discrete transistors. By mid-1959, with Elliott Fritz as its lead mechanical engineer, IBM had constructed the world's first fully automated production line for assembling alloy-junction transistors. The line comprised six assembly units, two ovens, and a welder and took about three hours to fully assemble a transistor [1].

The automated room-sized facility was a mechanical tour de force [8]. The assembly process started with sonic-driven Syntron bowls that vibrated out only properly dimensioned preformed components: rectangular metallic base frames with a hole for the single-crystal germanium disk, emitter and collector alloy spheres, and two contact whiskers and a mounting base. These were inserted into a machined carbon fixture that held them in place in boats that moved between stations by means of a conveyer belt monitored by photoelectric sensors. First, the emitter sphere was alloyed into the germanium disk in a hydrogen furnace; then the collector sphere was alloyed into the opposite side in a different furnace. In the zone-controlled furnaces, the germanium disk melted in a controlled fashion along its slow-dissolving <111>-oriented surface, recrystallizing a thin layer doped with the elements of the alloy dot. On further cooling, the alloy solidified into a bump that held the whisker wire contact. The boats were automatically disassembled, and then the whiskers were welded to the package leads. The transistor was extracted, acid-etched, washed, dried, hermetically vacuum-sealed in a can with a powder to stabilize the moisture content, and then tested.

IBM's automated line was theoretically capable of producing 3,600 transistors per hour, or 30 million transistors a year—far more than IBM needed. IBM had earlier decided not to manufacture electronic components. Since Texas Instruments (TI) was already supplying 90% of IBM's transistors, IBM shipped their entire automated production line to TI in October 1959 in exchange for three years' exclusive use [1]. TI later replicated the facility several times and became a major international supplier of germanium discrete transistors.

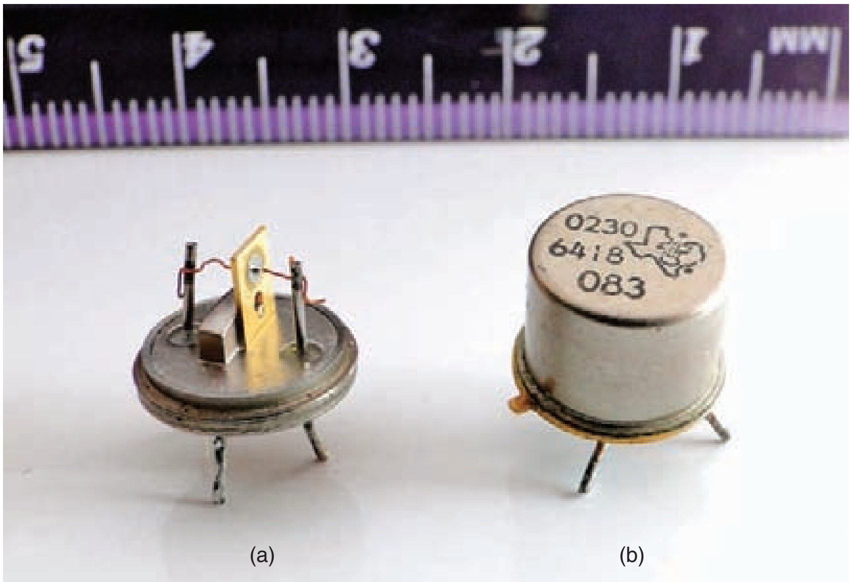

FIGURE 3: A germanium alloy-junction n-p-n transistor (IBM 083) showing (a) its internal structure and (b) its hermetically sealed TO-5 package, as manufactured by IBM's fully automated transistor production line transferred to TI in 1959. (Photo courtesy of Robert Garner.)

IBM's Standard Modular System (SMS) of Circuits and Packaging

While perfecting the automated transistor production line, IBM was also planning for the automatic manufacture of printed circuit boards (PCBs). Edward Garvey, after overseeing the design of 2,000 types of vacuum tube modules for the IBM 700-series computers, realized the need for an automated facility for assembling PCBs with solid-state components [1]. By 1958, with Logue's transistorized 604 cards as a starting point, the standardized engineering group in Endicott, New York, settled on the Standard Modular System (SMS) for electronics packaging. SMS defined two system packaging options, called Cube and Rolygon. The IBM 1401 was the first system to use the Cube packaging, and IBM's new large-scale 7000-series transistorized mainframes used the Rolygon packaging.

The SMS Cube packaging comprised 29-inch by 29-inch by 31-inch frame modules, with four large card "gates" in the front and four gates in the back. Cooling airflow was vertical, from bottom to top, with a fan in each gate. Frame modules could be stacked two high and two wide, for a total capacity of 32 gates—the configuration used by the 1401's "main frame" processing unit (see Figure 4). Gates easily swung outward 90° from the frame or slid out for convenient maintenance. A logic gate could hold up to 144 single-width SMS cards plugged into its single wire-wrapped backplane.

Figure 5 shows two sample SMS cards from the 1401: a typical single-width card and the less common double-width card. Single-width SMS cards were 2.6 in wide by 4.5 in long, with components mounted on one side. The cards had up to 16 contact pads. When a card was inserted into a backplane slot, the contact pad pressed against a thick gold dot on a phosphor-bronze spring. The cards employed a gold-nickel-copper metallurgic stackup with a thick gold

FIGURE 4: Restoration volunteer Ronald Williams and the 1401 processor "main frame" unit, which includes four SMS Cube frames with 24 gates of SMS cards (out of 32 total gate positions); the front panel with indicator lights, buttons, switches, and data paths; 4,000 positions of magnetic core memory; and hard-wired cable bundles to peripherals. The 1401 processor contains about 2,300 SMS cards with 10,600 alloy-junction transistors and 13,200 point-contact diodes. (Photo courtesy of Robert Garner.)

overcoat on top (100 µin, or 2.54 µm) that precluded small surface pores and prevented corrosion of the underlying layers. The thick gold layer eliminated the need for a special lubricant or corrosion inhibitor chemical on the contact surfaces.

To ensure the reliable interconnection of wires between backplane pins, wire-wrap technology was used, with stiff solid-core wires snuggly wrapped around rectangular backplane posts. No more than two wires were wrapped to a post, which made it easier for a field engineering change (EC) to alter backplane wiring. In IBM's production line, punched card readers controlled automated Gardner-Denver wire-wrapping machines.

Also during this time, IBM pioneered an early computer-aided design (CAD) system called automated logic diagram (ALD), which initially ran on IBM 704 and 705 mainframes. Logic designers began the CAD process by hand-sketching schematics that others then redrew onto standard forms and keypunched into cards. The ALD software performed basic rule checking (outputs only to inputs, proper logic levels, net loading, and so on) and printed a machine's full set of logic schematics on 17 inch by 22 inch C-sized paper with standardized symbols for logic gates and signal levels, page numbers for inputs and outputs, SMS card block frame locations, and EC information. Designers had to manually verify path delays and timing since the software did not perform timing analysis.

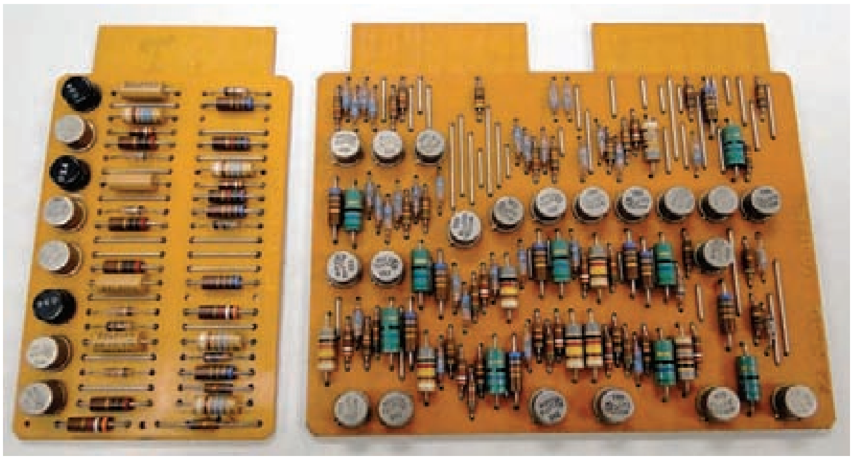

FIGURE 5: Single- and double-width SMS cards from the IBM 1401 Processing Unit. (Photo courtesy of Robert Garner.)

For computing circuits, IBM developed several transistor logic families in the latter part of the 1950s, including nonsaturating current mode switching and saturating complementary transistor diode logic (CTDL). Hannon Yourke at IBM invented current mode logic with a typical gate delay of only 60 ns [1], which was deployed in the scientific IBM 7090 and Stretch 7030 mainframes with 460-KHz clock cycle rates. With a slower typical gate delay of 250 ns, saturating CTDL was first deployed in the large-scale 250-kHz commercial IBM 7070. An earlier study had found that CTDL consumed 40% fewer transistors than current mode switching logic. Based on the IBM 7070 design experience, CTDL was selected for the 1401's logic circuits.

CTDL implemented and-or-inverter (AOI) compound logic gates where parallel input diodes implemented the AND function followed by an open-collector wired-OR inverting transistor output (see Figure 6). The n-p-n gates had active high inputs and active low outputs; the reverse was true of the p-n-p gates. The n-p-n gate outputs could only be connected to p-n-p gate inputs. Other standard logic elements included emitter followers for driving large loads, latches, oscillators, and single-shot triggers.

CTDL was robust and forgiving, and it handled large fan-ins and fan-outs with wires of up to about 12 ft.

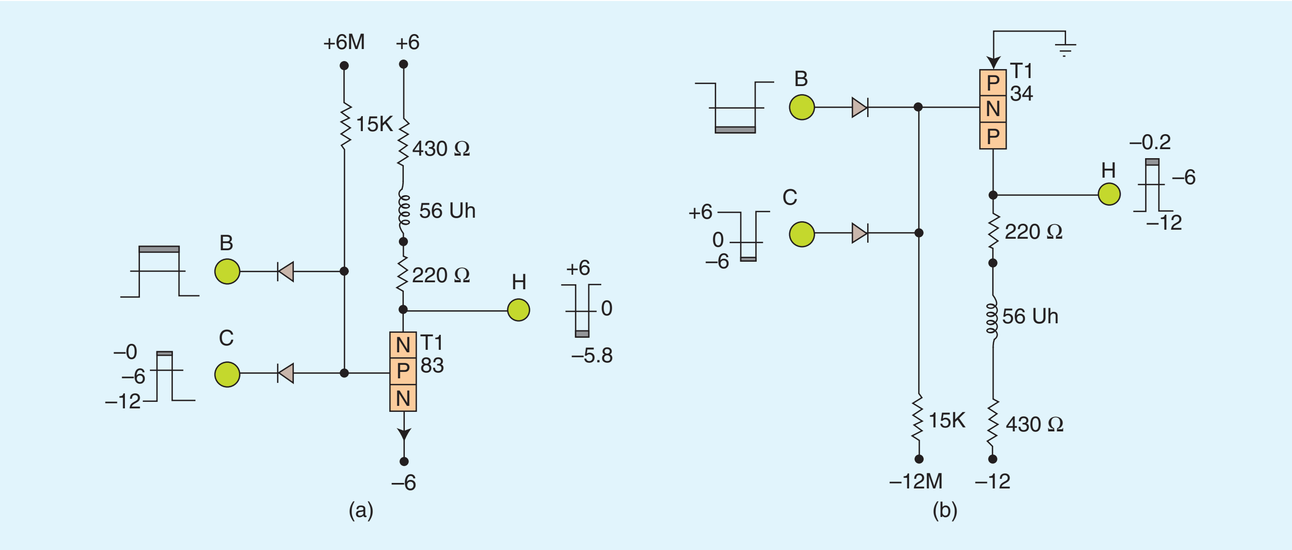

FIGURE 6: (a) A CTDL n-p-n active-high-input, active-low-output and-nor logic gate. (b) An n-p-n active-low-input, active-high-output and-or logic gate. The "H" output could be wired-OR'd to other gates without a load resistor. (Images courtesy of IBM.)

CTDL signal swings were 12 volts peak-to-peak: n-p-n gates received U levels centered about −6 V and generated T levels centered about 0 V; the situation was reversed for p-n-p gates. The 6-V offset allowed for 4.6 V of noise and load margin at each logic level. Of course, it was not always possible that an output signal would have the necessary level and logic polarity for a particular input, so 15–20% of the gates existed only to convert between U and T levels or between true and false polarities.

In 1958, IBM was already designing several large-scale computers using SMS technology: the scientific IBM 7090 (delivered in November 1959), the commercial IBM 7070 (delivered in March 1960), and the massive IBM 7030 Stretch supercomputer (delivered in May 1961) [2]. Stretch contained more than 18,000 single-width SMS cards and 4,000 double-width cards [9]. However, due to their high rental costs—an average of US$40,000 per month (or US$300,000 today)—only about 800 large-scale 7000-series computers were delivered to customers [2].

Since the early 1950s, IBM's CEO Thomas Watson, Jr. had led the company in a transition from electromechanical to electronic products. He wanted engineering to move more quickly from tubes to transistors, however. So in October 1957, IBM's director of engineering issued a decree that from that time on no products would employ vacuum tubes [1]. The dictate became known within IBM as "Solid-state in '58."

In meeting this challenge, by 1958 IBM had invented all the design and manufacturing technologies for delivering a high-volume transistorized computer: magnetic core plane manufacturing, a fully automated transistor assembly line, and automated PCB assembly. However, a plan for a mass-market computer in IBM's product lineup was proving to be elusive [10].

Origins of the IBM 1401

In 1954, the French firm Machines Bull introduced a combined calculator and accounting machine called the Bull Gamma III that outsold IBM products, particularly at French banks that frequently recalculated credit interest-rate charges. Christian de Waldner, the chairman of IBM France, initiated an in-depth planning and study effort on the part of IBM World Trade and domestic organizations that resulted in specifications for a combined transistorized calculator and accounting machine for the global market. Three IBM development laboratories in Paris (France), Böblingen (Germany), and Poughkeepsie (New York) held a competition in 1954 for the best design. The Paris lab's variable-word-length accounting machine (VWLAM) design was selected for the processing unit in the summer of 1955. For peripherals, the IBM Böblingen lab designed a high-speed stick-based printer and punched card reader.

The Paris processor design team, led by Maurice Papo and Eugene Estrems, at first wanted to design a variable-data-length stored-program computer like the IBM 705. However, the initial estimate by a U.S.-based

Since the early 1950s, IBM's CEO Thomas Watson, Jr. had led the company in a transition from electromechanical to electronic products.

costing department showed that the design could not achieve its price targets, and the Paris team inauspiciously reverted to plugboard-based control. Although the control panel layout was clever, it soon became an Achilles' heel.

Renamed the World-Wide Accounting Machine (WWAM), the prototype was operational in the Paris lab by 1957. Even though the WWAM used a plugboard for control, its projected price still came in significantly higher than the US$2,500 monthly rental target for an entry-level system (US$18,000 in today's currency). In addition, the high-speed German stick printer was deemed too costly to maintain [1].

In response to a 2004 ad in an IBM retirement newsletter, about 20 retired IBM employees stepped up to the challenge of restoring a 45-year-old 1401 acquired from Germany in mostly unknown condition.

In 1957, Francis O. Underwood of IBM Endicott's Advanced Systems Development Department (ASDD) was asked to join a newly formed Accounting Machines Department under Ralph Mork and establish its technical direction. He surveyed IBM's attempts to design an inexpensive transistorized accounting machine and decided that the WWAM had come closest with its familiar and flexible serial-by-character processing, decimal arithmetic, variable-length numbers and strings, print edit functionality, and up to 1,900 magnetic core memory locations for data [1]. However, examining the WWAM circuits more closely, he found that 45% of its electronics cost was only for communicating between its plugboard and internal logic. An avid proponent of stored-program computing, Underwood jettisoned the WWAM's plugboard and formulated a new instruction set for controlling its data paths. He called his new processor design SPACE, for stored-program accounting and calculating equipment—striking a responsive chord as Sputnik had just launched in October 1957.

Unlike existent stored-program computers with accumulators that had to be explicitly loaded from and stored into memory by software, Underwood instead defined a memory-to-memory architecture without using an accumulator, thereby reducing the number of instructions needed for accounting and business programs. He anticipated that the 1401's newly minted programmers would hand-code programs and manually assign instructions to memory locations, so he selected easy-to-recall instruction encodings and formats, such as *A* for add and *E* for edit. He also manually programmed several important algorithms, including the French banking algorithm, to validate that they fit in fewer than 1,400 memory locations for the entry-level 1401 system.

To achieve the ambitious entry-level rental price target of US$2,500 per month, Charles Branscomb, the Accounting Machine Department's new engineering program manager, worked tenaciously with IBM's computer technology groups to meet the company's requirements for low cost and high reliability. He selected the SMS Cube system of packaging and the CTDL circuit family. He also adopted a technologically advanced chain printer already under development as a standalone product for offloading mainframe printing (it became the IBM 1403). For punched card I/O, he elected to modify a mainstream reader punch unit, the IBM 088. In general, Branscomb resisted pressure to add additional features, but in early 1959 he agreed to incorporate an interface for controlling up to six magnetic tape units. Thus, by including magnetic tape support and keeping cost low, SPACE became the preferred design for offloading tape-to-print and card-to-tape operations from high-end mainframes [1].

By mid-1959, with the 40-person engineering team working night and day under engineering manager Jim Ingram, trial educational classes within IBM being spearheaded by marketing planner Sheldon Jacobs, and a prototype that achieved the entry-level price target up and running, the renamed IBM 1401 was poised to transform the business world with its low price, outstanding print quality, powerful magnetic tape subsystem, and the promise of a stored-program computer for the mass marketplace. But first Jacobs had to persuade IBM's skeptical forecasting department to sign off on the product launch. After debating exactly which features small business users really needed, IBM's doubtful forecasters reluctantly approved the 1401 as a revenue-neutral program just a few months before its announcement.

On 5 October 1959, the 1401 was presented via closed-circuit television to 50,000 participants in 102 cities. In the following September, the first 1401 was delivered to Time-Life in Chicago and by year end 100 systems had been manufactured in Endicott and delivered to customers (see Figure 7).

The 1401 was very successful. By 1965, half of the approximately 26,000 computers in the world were 1400-family machines—models 1401, 1410, 1440, 1460, and 7010 [2]. The total number of 1400-family computers peaked at about 15,000 systems in 1967 [2]. Although IBM's planning team had not considered the full impact of the tape option on customers before the announcement, customers soon took advantage of the tape-oriented 1401 systems to replace the long-term storage of data on endless numbers of punched cards. For example, Time-Life transferred 40 million punched card subscriber records to just several hundred magnetic tapes.

Characteristics and Features of the IBM 1401

Most 1401s were leased. Rental for an entry-level system was US$2,500 per month, although very few such systems were installed. The average system typically rented for about US$6,500 per month or cost US$500,000 to purchase (equivalent to US$45,000 and US$3.4 million today)—about a sixth of the purchase price of a large-scale mainframe.

Even though the 1401 was considered a small-scale computer, a full-size system had up to half a million discrete components, weighed up to four tons, and consumed up to 13,000 W. The 1401 processing unit used 10,600 germanium alloy-junction transistors and 13,200 germanium point-contact diodes on about 2,300 SMS cards interconnected with 5.5 mi of wire.

The reliability of the 1401 was renowned, and many systems operated around the clock. IBM had a large organization of customer engineers (CEs) who worked closely with users to maintain their systems. The typical 1401 system was out of service only a few times a year.

The 1401 processor sequentially processed 6-bit characters or decimal digits. A single character or digit was stored per memory position, and strings of characters or digits could be arbitrarily long (up to the size of memory). Instructions could operate on two operand strings in memory and write the result back into one of them. This memory-to-memory instruction format, without using an accumulator, reduced program size. It also reduced processor cost with only two operand registers and three memory address registers required in hardware logic. Memory ranged in capacity from an entry-level system with 1,400 positions to a maximum of 16,000 positions, with each position holding 8 bits: a 6-bit character or digit, a variable-length data and variable-length instruction flag called the "word mark," and a memory "check bit" with odd parity.

FIGURE 7: The IBM 1401 manufacturing and test production line in Endicott, New York, in the 1960s. (Image courtesy of IBM Archives.)

The 1401's processor cycle was 11.5 μs, for a clock rate of 87,000 cycles/s. A single character could be transferred per clock cycle, so the processing speed was well balanced to peripheral I/O rates. Given its digit-serial arithmetic, 50 cycles, or approximately 0.5 ms, were required to add two positive 20-digit numbers. Today's 4-GHz PC can add two 64-bit numbers about a million times faster. Assuming today's currency, a 1401 would cost about a thousand times more than a modern PC. This would make a PC's price-performance a billion times better than a 1401 when doing arithmetic.

The 1401 was originally designed with a 4,000-character maximum memory capacity but was soon expanded to 16,000 characters. The first 4,000 characters of memory (including a core plane for the punched card reader, card punch, and printer) were located in the 1401 processor's "main frame" cabinet. The 1406 Optional Storage Unit supported up to 12,000 additional characters of core memory in a single Cube cabinet. Core memory was priced at about 60 cents per bit (or US$24 per byte in today's currency)—300 million times more expensive than today's DRAM.

Inexpensive magnetic core memory was critical to the 1401's success. Since it was impractical to drive each of the core memory's half-select X and Y lines with a power transistor or several transistors as in the transistorized 604, a magnetic core switching matrix drove the memory's X and Y select lines, implementing both address decoding and amplification to supply the required one-amp current pulse to the selected memory core. The processor destructively read out core memory in the first half of an 11.5-μs cycle; then, in the second half, it restored the previous value or wrote a new value.

Pivotal to the 1401's success were its robust peripherals. Foremost among these was the IBM 1403 chain printer. Introduced together with the 1401, its high speed and enduring print quality made it an industry workhorse. The 1403 could print up to

132 columns at 600 lines/min, and its hydraulic carriage could skip over blank lines at 33 in/s under the control of a punched carriage control tape. Incorporating a new approach from IBM's earlier 150-lines/min wheel or stick printers, the 1403 simultaneously fired multiple hammers when the proper characters on its horizontally revolving chain were in position, slamming the paper, inked ribbon, and character slug together. Since the human eye does not notice minor sideways spacing variations between adjacent horizontal characters but is sensitive to vertical misalignment, 1403 printouts were easy to read. The 1403's chain assemblies were interchangeable, allowing the printing of different character sets. In order to drive the 1403's electromechanical hammers, a special 60-V high-power germanium power transistor was adopted.

Various models of the IBM 729 magnetic-tape vacuum-column drive unit, developed for the 7000-series mainframes, were able to transfer data at 15,000 to 62,500 characters/s, access tape records at 75 or 112.5 in/s, and rewind a 2400-foot, 13-million-character tape in less than 1 min. Lower-speed IBM 7330 tape drives were also offered. The IBM 1402 Reader Punch Unit could read cards at 800/min and punch at 250/min.

In 1961, the IBM 1405 RAMAC disk drive, with a 20 million character capacity and an 1800-r/min rotational rate, was offered for the 1401. This was followed in 1962 by the IBM 1311 Storage Drive, with removable 2-million-character disk packs.

Also in 1961, IBM offered optical and magnetic bank check readers as peripherals to the 1401. The IBM 1418 was one of the earliest optical character recognition (OCR) devices, scanning 420 documents/min with an OCR algorithm tuned for accounting machines, the 1403, and Selectric fonts. The IBM 1428 could read full alphanumeric data in what became the ANSI OCR A font. The IBM 1412 Magnetic Ink Character Reader (MICR) could read and sort bank checks with digits imprinted with magnetic ink—the ABA E13B font seen on the bottom of bank checks to this day.

Particularly during the 1950s, computer design was closely interwoven with rapidly evolving circuit technologies and techniques.

To help achieve the low entry-level cost, the 1401 processor cabinet included controllers for the 1403 printer, 1402 card reader/punch, and optional tape drives. Peripherals used the processor data paths to access memory, so instruction processing stopped during most peripheral operations. Later, an "overlap" feature enabled punched cards to be read while the processor executed instructions. IBM provided documentation to enable customers to construct custom interfaces for their peripherals.

The 1401 employed several interesting analog approaches to lower costs. The magnetic tape drives transmitted low-voltage tape read head signals through up to 100 ft of daisy-chained single-ended coaxial cables to the processor, where the read amplifiers, dual-level peak detection circuits, and clock recovery circuits were located. To reduce costs further, the pulses generated by the 1402's card reader brushes wrote character data over a long cable directly into the magnetic cores in the 1401 frame. To increase reliability, the system employed ferroresonant transistorized power supplies tuned either to 50 or 60 Hz to filter out the noisy grid power prevalent around the world. While large-scale computers generally required custom raised-floor and overhead air-exhaust facilities, the 1401 could be situated in a normal air-conditioned office or small room, with the cables lying on the floor or strung overhead.

The 1401 contributed to the growth of programming as a profession and software as an industry. Thousands of accounting-machine users were retrained as programmers, and several books covered 1401 programming. IBM offered Autocoder and Symbolic Programming System (SPS) assemblers for machine-level programming, FORTRAN, COBOL, and report program generator (RPG) compilers, and sort and I/O utilities. There was no operating system for the 1401 (IBM later released one for the 1410). IBM, together with one of the earliest software user groups, SHARE, offered hundreds of privately developed 1401 applications for multiple industries in business, engineering, mathematics, and science.

1401 Competition and Succession

In late 1963, Honeywell challenged IBM's market dominance by announcing the faster and more capable H200 processor, which had a design similar to that of the 1401 (albeit with less robust peripherals). The H200 was offered with so-called "Liberator" software that could run 1401 programs unmodified and more quickly than a 1401. The 1401 was the world's most popular computer at the time, and this threat caught IBM's management by surprise [11]. By that time, IBM was far along in orchestrating the succession and unification of its many incompatible computer lines, an effort begun in 1961. That significant planning effort resulted in the April 1964 announcement of the System/360 (S/360), which consolidated software, peripherals, and support in one compatible and scalable computer family [11].

One key technology used in the S/360 was a flexible control store that implemented the S/360 instruction set via microcode instructions, enabling the emulation of other computer instruction sets. When the Honeywell H200 was announced, the S/360 Model 30 architects quickly made enhancements to efficiently emulate the 1401 instruction set, thus enabling the Model 30 to hold the fort against the H200 [11].

Although 1400-family development wound down with the S/360 announcement in 1964, 1400s continued to outnumber S/360s until about mid-1967 [2]. The 1401 was offered by IBM until 1971, and PC-based simulators are still available today. There is a reasonable chance that an IBM mainframe somewhere is still running a 1401 application from decades ago.

1401 Miscellanea

In Endicott, New York, in 1960, Edward Rent performed an initial analysis of optimal logic card sizes for the IBM 1410, the first follow-on to the 1401. He measured the ratio of the number of logic blocks in SMS cards in four 1401 chassis gates to the number of card edge signal connectors. The resulting straight-line relationship on a log-log graph was the start of what became known as Rent's rule: Given the number of logic gates or blocks in a particular circuit, one can calculate an estimated number of connections or signal pins needed to communicate with them [12].

In 1964, AT&T, IBM, and the French postal service demonstrated the first transatlantic transmission of computer data via Telstar, the first commercial communications satellite. IBM engineers using an IBM 1009 Data Transmission Unit on a 1401 in Endicott and a similar setup in the Le Gaude lab near Nice, where the IBM Paris lab had moved, were able to transmit data at 2,000 b/s over a voice-grade phone line [13].

Just for fun, the 1401 could play musical tunes via software that timed the firing of 1403 print hammers.

Just for fun, the 1401 could play musical tunes via software that timed the firing of 1403 print hammers. Other programs, by executing particular code sequences, modulated a 1401's radio wave emissions, which a nearby AM radio could easily receive via electromagnetic interference (EMI).

The 1401 resurfaced in popular culture in 2001 when a young Icelandic composer, Jóhann Jóhannsson, scored the symphonic composition *IBM 1401: A User's Manual*. He had been inspired by a 1971 recording of 1401 radio music made by his father, a customer engineer for Iceland's first computer, a 1401, during the machine's decommissioning ceremony [14]. Jóhannsson's composition may be the only human-composed music written for and dedicated to a computer.

In the 1964 movie *Dr. Strangelove*, actor Peter Sellers made his opening appearance examining an IBM 1403 printout from a tape-oriented IBM 1401 used as an I/O spooler for a large-scale IBM 7090 system.

1401 Restoration Project at the Computer History Museum

Two complete IBM 1401 systems have been brought back to life by a team of about 20 volunteers at the Computer History Museum (CHM) in Mountain View, California—mostly IBM engineers who had previously worked on 1401s in design, test, and customer engineering (see Figures 8 and 9). The successful restoration, after nearly 500 work sessions and 20,000 hours [15], highlights the strength of the 1401's design and the reliability of its mechanical and solid-state components nearly 50 years after its manufacture.

In response to a 2004 ad in the San Jose, California, IBM retirement newsletter, about 20 retired IBM employees stepped up to the challenge of restoring a 45-year-old 1401 acquired from Germany in mostly unknown condition. The CHM acquired a second, 47-year-old 1401 in 2008 from Connecticut that was in better condition. Both systems had originally been operated continuously for six and ten years, respectively, by insurance companies; private entrepreneurs had then purchased

FIGURE 8: View of the 1401 restoration room at the CHM. The Connecticut 1401 is to the left of center, and the German 1401 is on the right. From left to right: Ron Williams, Don Luke, Joe Preston, Ed Thelen, George Ahearn, Frank King, Glenn Lea, and Bob Erickson (at an IBM 513 Reproducing Punch). An IBM 026 Printing Card Keypunch and a 077 Collator are to the right. (Photo courtesy of Robert Garner.)

FIGURE 9: Members of the 1401 restoration team in period dress. From left to right: Bill Flora, Joe Preston, Sam Sjogren, Jeff Stutzman, Ed Thelen, Bob Feretich, Ron Williams, Frank King, Matthias Goerner, Bob Erickson, Robert Garner, George Ahearn, Don Luke, Allan Palmer, Ron Crane, Stan Paddock, and Bill Newman. (Photo courtesy of Robert Garner.)

them to provide billing services for small businesses. The German system operated until 1977 and was then stored in an outdoor auto garage for 27 years. The U.S. system had operated until 1995 in the air-conditioned basement of a small residence. Both systems were fully configured with 16,000 memory locations and four IBM 729 tape drives. IBM's Almaden Research Center and 14 Silicon Valley donors generously contributed funds for the acquisition of these two 1401 systems.

After acquiring a 60-Hz-to-50-Hz power converter, restoration of the German 1401 proceeded for three years of earnest oscilloscope- and schematic-based debugging. The restoration team diagnosed 130 defective SMS cards. The Connecticut 1401, mothballed for 18 fewer years than the German system, yielded 25 failed SMS cards. Most of the card failures were due to corroded ferrous transistor and diode leads; weak or leaky transistors; open, shorted, or broken diodes; and latches acting like one-shots. The number of faulty SMS cards corresponded to an annual failure rate of only about 0.125% per year, not unreasonable considering high-humidity storage. The team located "new old stock" transistors from Internet sellers. The team also designed several new hardware devices. One was a USB interface that allowed small binary files stored on a laptop to be punched directly on an IBM 026 card punch. Another was a 729 tape drive emulator built around an embedded PC and analog electronics used to restore the 1401's tape adapter unit (TAU) logic, upload binaries into the 1401, and emulate 729 tape drives.

Remarkably and thankfully, there have been no problems with the wire-wrap or backplane wires, the long signal wires interconnecting chassis gates, or the long signal and power cable bundles between the various peripheral units. The SMS card traces with their uncommonly thick gold overcoat, analyzed by IBM Poughkeepsie's Materials and Process Engineering group in 2007, have proven extraordinarily reliable. Nearly all SMS cards were left undisturbed even though the 1401s were transported to the CHM via trucks and ocean cargo ships and were stored in less-than-ideal environments. Intermittent contact failures have been essentially zero nearly 50 years after the date of manufacture.

FIGURE 10: A current versus voltage trace of a defective germanium alloy-junction n-p-n transistor, illustrating a hysteresis curve likely caused by a surface inversion. The I-V curve shows collector-emitter voltage on the abscissa versus current on the ordinate at four different base currents. Such "loopy" I-V curves, measured with the collector voltage alternating from 2 Hz up to 1 MHz, appear to exhibit "memristor" behavior, first theoretically defined by Leon Chua in 1971 [17]. (Photo courtesy of Robert Garner.)

The 1401 restoration volunteers analyzed defective components after troubleshooting faulty system behavior. A surprising phenomenon was observed in certain defective transistors: a "loopy" or hysteretic collector current versus voltage curve (see Figure 10). This phenomenon was first reported in the 1950s and was thought to be caused by moist air affecting the germanium surface [16]. The loopy I-V curves appear in our defective transistor measurements with collector-emitter voltages alternating from 2 Hz up to 1 MHz, and the effect can persist for up to 0.5 s after scanning stops. The phenomenon appears to be characteristic of the "memristor," first theoretically defined by Leon Chua in 1971 [17]. In 2008, HP Laboratories reported observing memristor hysteresis caused by ionic transport in thin-film TiOx devices [18]. Perhaps these defective "loopy" germanium transistors were also unknowingly exhibiting memristor behavior back in the 1950s?

Summary

Businesses and institutions throughout the world used the IBM 1401 in the 1960s to process rapidly growing amounts of information. By the middle of the decade, one out of every two computers in the world was an IBM 1400-family machine, delivering on the promise of a reliable, cost-effective, high-volume transistorized computer. The 1401 heralded a widespread transition from plugboard-based unit record machines to ubiquitous stored-program computing, now taken for granted with its easy sharing and distribution of software applications. The 1401 provided IBM with the first realistic glimpse of the size and importance of the computer market and changed the world.

Computer History Museum volunteers, over the course of the past five years, have restored two tape-oriented IBM 1401s. The operational systems continue to impress museum visitors and attract new volunteers to keep them running, write new demonstration programs, and learn more about the 1401's electronic and mechanical technologies that are not so miniaturized that they can't be easily repaired.

The Computer History Museum is dedicated to the preservation and celebration of the computing revolution and its worldwide impact on the human experience. If you have artifacts or stories of the information age or are interested in volunteering, you are invited to visit the museum in person or its Web site, www.computerhistory.org.

Acknowledgments

The first author, Robert Garner, is indebted to the first-person insights and feedback on various parts of this paper obtained in e-mails and conversations with original 1401 hardware team members Francis Underwood, Charles Branscomb, Sheldon Jacobs, Jim Ingram, Jud McCarthy, John Pokoski, George Ahearn, WWAM designer Maurice Papo, and IBM circuits pioneer Joseph Logue; computer historians Fredrick Brooks, Emerson Pugh, and Jack Palmer; 1401 restoration volunteers and retired IBM test and customer engineers Ron Williams, Bob Erickson, Frank King, Allen Palmer, Bill Flora, and Don Luke; 1401 restoration volunteers Ed Thelen, Grant Saviers, Bob Feretich, and Stan Paddock; analog expert volunteers Ronald Crane and Bill Newman; CHM senior curator Dag Spicer; and reviewers Ronald Mak, Dick Weaver, Mitchell Marcus, and David Laws. All errors and omissions are due entirely to the authors' oversights.

References

[1] C. J. Bashe, L. R. Johnson, J. H. Palmer, and E. W. Pugh, *IBM's Early Computers.* Cambridge, MA: MIT Press, 1986.
[2] E. C. Berkeley, Ed., "Monthly computer census," *Comput. Automat.*, Dec. 1959–Dec. 1969.
[3] M. H. Weik. (1961, Mar.). A third survey of domestic electronics digital computing systems. Ballistic Research Laboratories, Aberdeen, MD. Report No. 1115 [Online]. Available: http://ed-thelen.org/comp-hist/BRL61.html
[4] E. W. Pugh, *Memories That Shaped an Industry.* Cambridge, MA: MIT Press, 1984.
[5] J. C. Logue, "Transistor switching circuits," in *Handbook of Semiconductor Electronics,* 1st ed., L. P. Hunter, Ed. New York: McGraw-Hill, 1956, ch. 15, pp. 12–13.
[6] J. C. Logue, "From vacuum tubes to very large scale integration: A personal memoir," *IEEE Annals Hist. Comput.,* vol. 20, no. 3, pp. 55–68, July–Sept. 1998.
[7] G. D. Bruce and J. C. Logue, "An experimental transistor calculator," *AIEE Elect. Eng.*, vol. 74, pp. 1044–1048, Dec. 1955.
[8] T. J. Leach, "Automated assembly of alloy-junction transistors," *Electronics*, vol. 25, pp. 57–61, Mar. 1960.
[9] W. Buchholz, Ed., *Planning a Computer System, Project STRETCH.* New York, NY: McGraw-Hill, 1962.
[10] C. J. Bashe, W. Buchholz, G. V. Hawkins, J. J. Ingram, and N. Rochester, "The architecture of IBM's early computers," *IBM J. Res. Develop.*, vol. 25, no. 5, pp. 363–375, 1981.
[11] E. W. Pugh, L. R. Johnson, and J. H. Palmer, *IBM's 360 and Early 370 Systems.* Cambridge, MA: MIT Press, 1991.
[12] M. Y. Lanzerotti, G. Fiorenza, and R. A. Rand, "Microminiature packaging and integrated circuitry: The work of E. F. Rent," *IBM J. Res. Develop.*, vol. 49, no. 4/5, pp. 777–803, 2005.
[13] (1964, Oct. 25). IBM Press Release, Endicott, NY [Online]. Available: http://www.ed-thelen.org/1401Project/1401Origins.html#IBM-Endicott-Nice-Telestar-1964
[14] J. Jóhannsson. (2005) Available: www.ausersmanual.com
[15] 1401 Restoration Project Web site. Available: http://www.ed-thelen.org/1401Project/1401RestorationPage.html
[16] H. C. Montgomery and W. L. Brown, "Field-induced conductivity changes in germanium," *Phy. Rev.*, vol. 103, no. 4, Aug. 15, 1956, pp. 866–870.
[17] L. O. Chua, "Memristor—The missing circuit element," *IEEE Trans. Circuit Theory*, vol. 18, no. 5, pp. 507–519, Sept. 1971.
[18] D. B. Strukov, G. S. Snider, D. R. Steward, and R. S. Williams, "The missing memristor found," *Nature,* vol. 453, no. 6932, pp. 80–83, 2008.

About the Authors

Robert Garner received an M.S.E.E. degree from Stanford University in 1977. He started his Silicon Valley career at Xerox System Development in Palo Alto in 1977. In 1981, he transferred to the Xerox Palo Alto Research Center. In 1984, he joined the start-up company Sun Microsystems as the lead architect of its SPARC (RISC) architecture and codesigned its first SPARC product, the Sun-4/200 Workstation. In 1998, he joined the start-up company Brocade Communications as director of hardware engineering, where he was responsible for FibreChannel ASIC and switching products. In 2001, he joined the IBM Almaden Research Center in San Jose, where he codesigned the experimental 3-D IceCube server. He currently manages an advanced-redundancy Petascale storage subsystem software project. In 2004, he also volunteered at the Computer History Museum to lead the restoration of an IBM 1401 computer. He can be reached at robgarn@us.ibm.com.

Frederick (Rick) Dill first worked for IBM in 1954 as a summer student and returned after completing his Ph.D degree in electrical engineering from Carnegie Tech in early 1958, where he used the IBM 650 vacuum tube computer. He is a Fellow of the IEEE, former president of the Electron Devices Society, and a member of NAE. Most importantly, he remembers building gallium arsenide transistors with his own hands trained by the technicians who built the prototypes for the 1401 transistors. He was fortunate to live when the transistor was new and history was happening.