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Babbage

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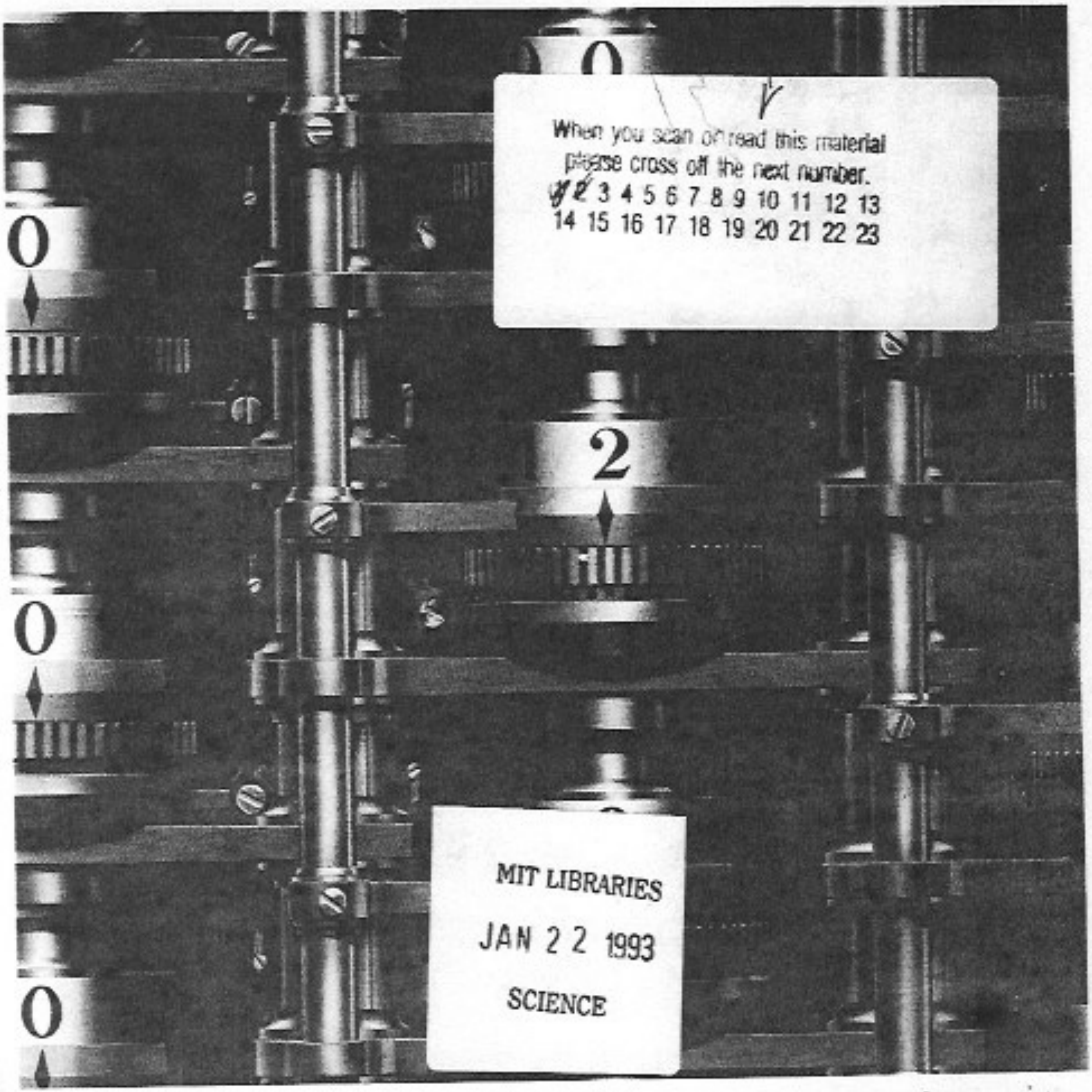


A calculating engine was built more than a century after it was attempted by Charles Babbage. It works.

Redeeming Charles Babbage's Mechanical Computer

A successful effort to build a working, three-ton Babbage calculating engine suggests that history has misjudged the pioneer of automatic computing

by Doron D. Swade

Charles Babbage is celebrated as the great ancestral figure in the history of computing. The designs for his vast mechanical calculators rank among the most startling intellectual achievements of the 19th century. Yet Babbage failed in his efforts to realize those plans in physical form. Histories of computing routinely assert that Babbage faltered primarily because the demands of his devices lay beyond the capabilities of Victorian mechanical engineering. Curiously, no contemporary evidence supports that view.

In 1985 my colleagues and I at the Science Museum in London set out to resolve or at least illuminate the question by building a full-size Babbage computing engine based on his original designs. Our endeavor finally bore fruit in November 1991, a month before the bicentenary of Babbage's birth. At that time, the device—known as Difference Engine No. 2—flawlessly performed its first major calculation. The success of our undertaking affirmed that Babbage's failures were ones of practical accomplishment, not of design.

CHARLES BABBAGE sat for this daguerreotype around 1847, the year he began work on Difference Engine No. 2.

Those failures have become inextricably associated with his creative genius. Babbage, proud and principled, was famed for the vigor and sarcasm of his public denunciations of the scientific establishment. The demise of his engine project added a sense of injustice, bitterness and even despair to his celebrated diatribes. Since then, he has acquired an image of testiness and eccentricity; the first biography of Babbage, written by Maboth Moseley and published in 1964, was titled *Irascible Genius: A Life of Charles Babbage, Inventor*. Our work at the Science Museum emphasizes a distinctly different side of Babbage: a meticulous inventor whose designs were hugely ambitious but well within the realm of possibility.

DORON D. SWADE is both an electronics engineer and a historian of computing. He has been senior curator of the computing and control section of the Science Museum in London since 1985 and has published articles on curatorship and on the history of computing. He has recently written two books: *Charles Babbage and His Calculating Engines*, which accompanies the Babbage exhibition that Swade curated, and, in collaboration with Jon Palfreman, *The Dream Machine: Exploring the Computer Age*, a companion to the television series of the same name. Swade led the project to construct a full-scale Babbage calculating engine.

Babbage's desire to mechanize calculation arose from the exasperation he felt at the inaccuracies in printed mathematical tables. Scientists, bankers, actuaries, navigators, engineers and the like relied on such tables to perform calculations requiring accuracy to more than a few figures. But the production of tables was tedious and prone to error at each stage of preparation, from calculation to transcription to typesetting. Dionysius Lardner, a well-known popularizer of science, wrote in 1834 that a random selection of 40 volumes of mathematical tables incorporated 3,700 acknowledged errata, some of which themselves contained errors.

Babbage was both a connoisseur of tables and a fastidious analyst of tabular errors. He traced clusters of errors common to different editions of tables and deduced where pieces of loose type had been incorrectly replaced after falling out. On one occasion, he collaborated with John Herschel, the renowned British astronomer, to check two independently prepared sets of calculations for astronomical tables; the two men were dismayed by the numerous discrepancies. "I wish to God these calculations had been executed by steam!" Babbage exclaimed in 1821.

Mechanical computers should, Babbage thought, offer a means to eliminate at a stroke all the sources of mistakes in mathematical tables. He envisioned a machine that not only would calculate flawlessly but would eradicate transcription and typesetting errors by automatically impressing the results of its calculations onto papier-mâché strips or plates of soft metal. A printed record could then be generated directly from those plates, thereby eliminating every opportunity for the genesis of errors.

In 1822 Babbage built an experimental model intended to carry him toward his goal. He called his mechanical calculator a "difference engine" because it is based on a mathematical principle known as the method of finite differences. The method permits one to determine successive values of polynomial functions using only addition [*see box on page 90*]. Multiplication and division, which are far more difficult to mechanize, are not necessary. Because the value of the function at each step is calculated based on its predecessor, a correct final result imparts a high degree of confidence that all previous values are also correct.

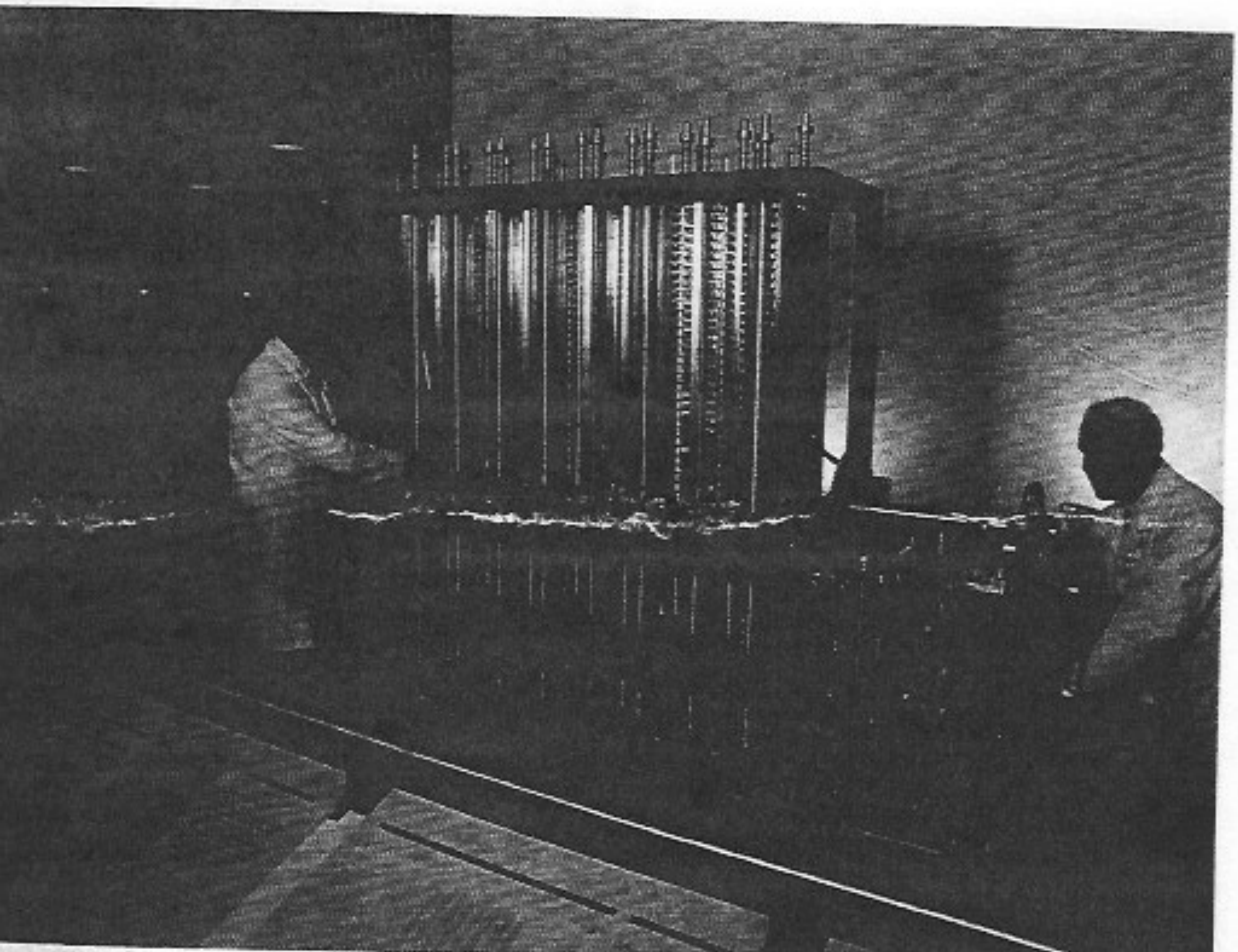
For economy of design, Babbage's difference engines use the decimal number system rather than the binary system common to modern electronic computers. Each digit in a multidigit number is represented by a toothed gear wheel, or figure wheel, engraved with decimal numerals. The value of each digit is represented by the angular rotation of the associated figure wheel. The engine's control mechanism ensures that only whole-number values, represented by discrete positions of the figure wheels, are valid. Babbage boasted that his machines would produce the correct result or would jam but that they would never deceive.

Babbage's most ambitious venture to construct a full-scale calculating device was devoted to the ill-fated Difference Engine No. 1. His efforts foundered in 1833 after a decade of design, development and component manufacture, not to mention vast expense. The project collapsed after a dispute between Babbage and his chief engineer, Joseph Clement, over payment for relocating the machining works. Outwardly at least, technology did not feature in the disagreement. The question that has remained tantalizingly unresolved is whether the circumstances surrounding the collapse of the project concealed the technical or logical impossibility of Babbage's schemes.

Difference Engine No. 1 consists of a basic adding element, repeated many times over in an arrangement that embodies the method of differences. The size and complexity of the engine are monumental: the design calls for roughly 25,000 parts; the assembled machine would measure eight feet high, seven feet long and three feet deep; and it would weigh several tons. The project, which was funded by the British government, was also enormously expensive. When Clement's last bill was paid in 1834, the cost totaled £17,470. For comparison, the steam locomotive John Bull, built in 1831, cost all of £784.

Clement completed about 12,000 of the 25,000 parts required for Difference Engine No. 1, most of which were later melted down as scrap. The British government finally withdrew from the project in 1842, partly on the advice of George Biddell Airy, Astronomer Royal, who pronounced Babbage's engine "worthless." The failure to complete the difference engine was the central trauma in Babbage's scientific life; it is a topic he returns to repeatedly in his writings as though unable to reconcile himself to the dismal outcome.

The years of work on Difference Engine No. 1 did produce one noteworthy, tangible result. In 1832 Clement assembled a small section of the engine, con-



IFFERENCE ENGINE NO. 2 was constructed in public view at e Science Museum in London. Here the two engineers who ilt it, Barrie Holloway (*left*) and Reg Crick (*right*), perform some essential adjustments. Babbage also designed a printing mechanism for the difference engine, but because of limited time and money, the printer has not yet been built sisting of about 2,000 parts, as a demonstration piece. This finished part of the unfinished engine is one of the finest examples of precision engineering of the time and works impeccably to this day.

The demonstration piece is the first known automatic calculator. Unlike the desktop calculators of the time, the engine, once set up, did not rely on informed human intervention. Thus, an operator could achieve accurate results without any understanding of the logical or mechanical principles involved. The opportunity to speculate about machine intelligence was not lost on Babbage and his contemporaries. Harry Wilmot Buxton, a younger colleague with whom Babbage entrusted many of his papers, wrote that "the wondrous pulp and fibre of the brain had been substituted by brass and iron; he [Babbage] had taught wheelwork to think."

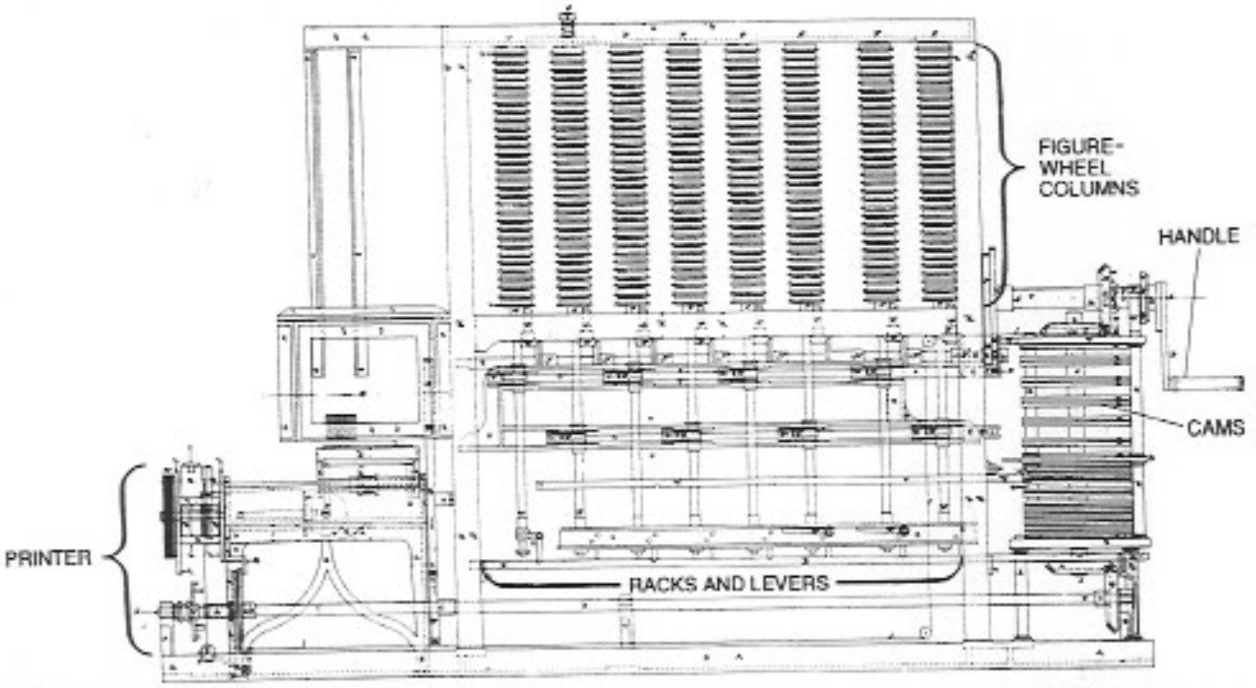
Despite its impressive capabilities, the difference engine could perform only one fixed task. Babbage's reputation as a computer pioneer largely rests on another, more sophisticated device—the Analytical Engine, conceived by 1834. He intended the Analytical Engine as a general-purpose programmable computing machine, whose features are startlingly similar to those of modern electronic computers. It had a basic repertoire of operations (addition, subtraction, multiplication and division) that it could execute in any sequence. The internal architecture of the machine featured a separate "store" and "mill," equivalent to the memory and processor in a modern computer. The separation of store and mill has been a dominant design feature of electronic computers since the mid-1940s.

The Analytical Engine could be programmed by using punched cards, a technique previously used in the Jacquard loom to control patterns of woven thread. The Analytical Engine could take alternative courses of action depending on the result of a calculation, enabling it to perform complex functions. Babbage intended the machine to be able to handle up to 50-digit input numbers and 100-digit results; the output could be printed, punched or plotted.

Although historians customarily refer to the Analytical Engine as if it were a physical thing, it is actually a series of unbuilt designs that Babbage refined at intervals from 1834 until his death in 1871. Demoralized by the fate of Difference Engine No. 1, he made no serious attempt to construct a full-scale Analytical Engine. A small experimental part of the mill that was still incomplete at the time of his death, along with

How Babbage's Difference Engines Work

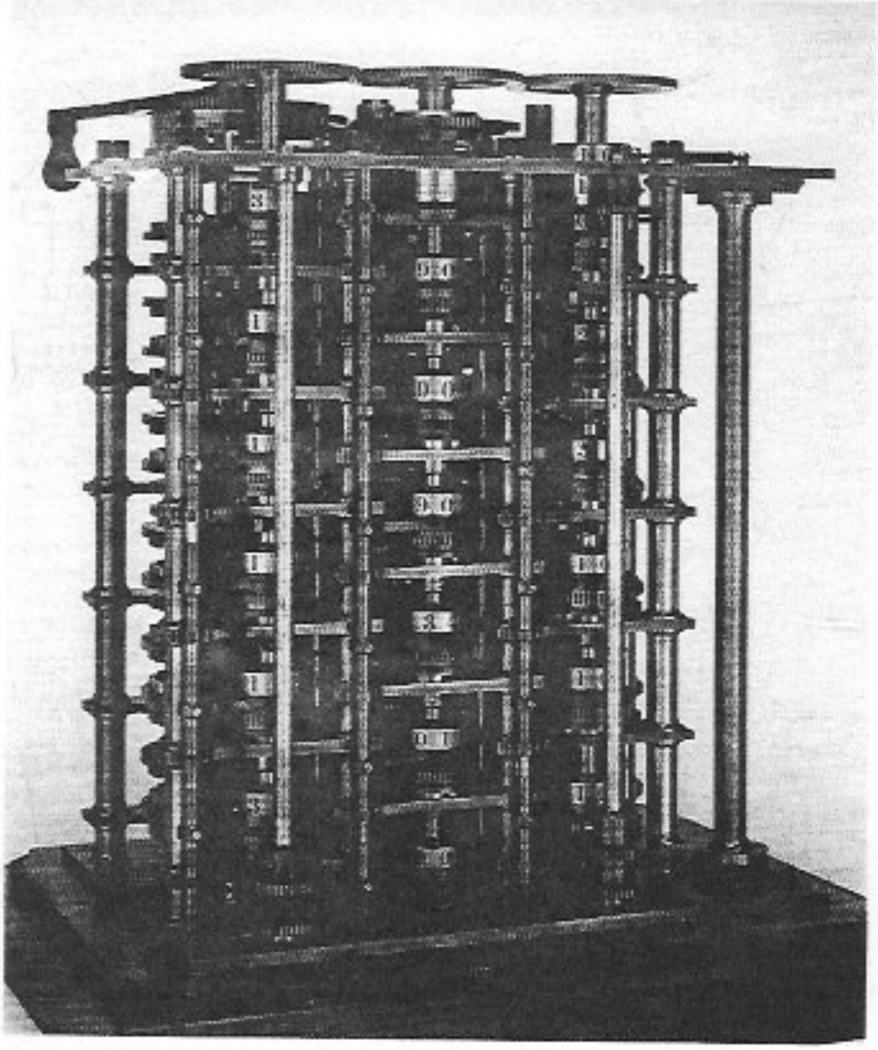
Shown below is one of Babbage's 20 main drawings of Difference Engine No. 2, which he drafted in 1847. The machine is operated by means of the handle on the right. Turning the handle rotates a vertical stack of 14 pairs of cams that determine the action and timing of the calculating cycle. Numbers are stored and operated on in eight vertical columns, each of which contains 31 engraved figure wheels. The least significant digit of a number is stored at the bottom of the column, the most significant digit at the top. The initial values for a calculation are entered by unlocking the figure wheels and rotating each one by hand to the appropriate decimal value. Below the figure-wheel columns are a set of racks and levers that, when activated by links from the cams, lift, lower and turn the vertical axes, thereby carrying out the addition of differences. Difference Engine No. 2 does not add numbers in sequence from right to left, as one might expect. Instead values from odd-numbered columns are added to even-numbered columns during the first half-cycle; even-numbered columns are then added to odd-numbered columns during the second half-cycle. This technique significantly reduces the time required for a calculation. A similar approach, known as pipelining, is used in modern electronic computers. The printing assembly, located at the left, is directly coupled to the last column of figure wheels, which bear the final result of the calculation. Each turn of the handle produces one 30-digit value in the table of differences and automatically prepares the machine to generate the next number.



another fragment later built by Babbage's son, Henry Prevost Babbage, are the only significant remains of his grand designs.

Work on the Analytical Engine forced Babbage to think about how to develop mechanisms capable of automatic multiplication and division, all regulated by a complex control system. The solutions to those problems inspired him to design a simpler and more elegant difference engine, Difference Engine No. 2. Although the machine calculates to a precision of 31 figures, 10 digits more than Babbage envisaged for Difference Engine No. 1, it contains only one third as many parts. Babbage drew up detailed plans for the second machine between 1847 and 1849 and offered them to the government in 1852 but received no encouragement. So things stood for nearly a century and a half.

During several visits to London beginning in 1979, Allan G. Bromley of the University of Sydney in Australia examined Babbage's drawings and notebooks in the Science Museum Library and became convinced that Difference Engine No. 2 could be built and would work. I had independently read of Babbage's hapless fate and become deeply puzzled as to why no one had tried to resolve the issue of Babbage's failures by actually building his engine.



WORKING PART of Difference Engine No. 1, assembled by Joseph Clement in 1832, is the first known automatic calculator. Its flawless operation strongly supports Babbage's conviction that building a full-sized engine was a practical prospect.

In 1985, shortly after my appointment as curator of computing, Bromley appeared at the Science Museum carrying a two-page proposal to do just that. He suggested that the museum attempt to complete the machine by 1991, the bicentenary of Babbage's birth. Bromley's proposal marked the start of a six-year project that became something of a personal crusade for me. The saga of our effort to construct the difference engine is one worthy of Babbage himself. We embarked on a complex engineering project that took us into unknown technical territory and confronted us with mechanical conundrums, funding crises and the intrigues inherent in any major venture.

Difference Engine No. 2 was clearly the engine of choice for the project. The associated set of drawings is intact, whereas those for Difference Engine No. 1 show regrettable gaps. Difference Engine No. 2 is also a more economic design. Cost and time constraints argued in favor of ignoring the printer and concentrating on the rest of the engine. The printer is composed of about 4,000 parts and would be a sizable engineering project in its own right.

The documentation for Difference Engine No. 2 consists of 20 main design drawings and several tracings. As we pored over those drawings, my colleagues and I discovered several flaws in the plans, in addition to those identified by Bromley. One major assembly appears to be redundant. Other mechanisms are missing from the design. For example, the initial values needed to begin a calculation are entered by unlocking the columns and manually rotating each of the freed figure wheels to the appropriate positions. Babbage omitted a means of locking the columns after they were set, so the setting-up procedure was self-corrupting.

The most serious design lapse concerned the carriage mechanism. This crucial component ensures that if, in the course of an addition, the value on a figure wheel exceeds 10, then the next higher figure wheel (indicating numbers 10 times larger) advances one digit. The most extreme test of the carriage mechanism occurs when a 1 is added to a row of 9's. Babbage solved the carry problem in an exquisitely innovative manner. During the first part of the calculating cycle, the engine performs a 31-digit addition without carrying the 10's, but every figure wheel that exceeds 10 sets a spring-loaded warning device. In the second part of the cycle, each armed warning device allows a rotating arm to advance the next higher figure wheel by one position.

Unfortunately, the configuration of the carry mechanism shown in Babbage's design drawings is unworkable. The direction of rotation of the figure wheels is incorrect, and the warning-and-carry mechanism could not function as drawn. The source of these shortcomings stimulated considerable speculation. We considered the possibility that errors were introduced deliberately as security against industrial espionage. More likely, some flaws were design oversights, and others were inevitable drafting and layout errors.

None of the design problems we found in Difference Engine No. 2 compromised its overall logic or operational principles, and we managed to devise solutions for all. Unnecessary mechanisms were omitted. The missing locking assemblies for the figure wheels were devised and, where necessary, their motions derived from those of neighboring pieces. Bromley solved the carry-mechanism problem by mirror-reversing the incorrectly drawn parts and altering their orientation. The introduction of a four-to-one reduction gear in the drive allayed skepticism about whether the massive Difference Engine No. 2 could be driven by hand. This change made the drive handle four times easier to turn but caused the engine to run four times slower.

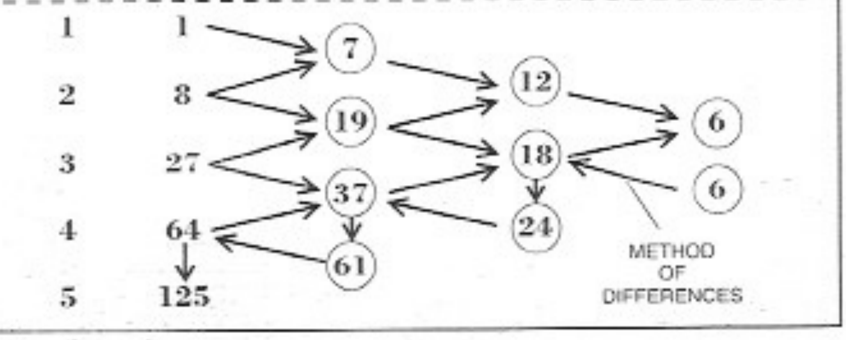
Implementing the solutions raised a significant philosophical dilemma. Could we make these alterations without compromising the historical authenticity of the result and, with it, the mission of proving that Babbage's engines were logically and practically sound? We solved this problem by adhering to Babbage's own design practices and strictly confining ourselves to techniques or devices available to Babbage. We also planned the revisions to Babbage's design so that every mechanism we added could be easily removed.

In 1989 we built a small trial assembly at the Science Museum to verify the logic of the basic adding element and to confirm that the carry mechanism operated correctly. The assembly adds a two-digit number to another two-digit number and takes account of any carry from units to tens and from tens to hundreds. The finely finished device went a long way toward convincing sponsors and colleagues that our project involved an engineering aesthetic as well as an intriguing historical thesis. The trial piece later proved an invaluable aid for visualizing the machine's operation and for testing the first sample parts.

Mathematical Principles of the Difference Engines

Babbage's difference engines are so called because they use the method of finite differences to find the value of certain mathematical expressions. The method is used below to produce the table of cubes ($y = x^3$). The first difference is found by subtracting successive pairs of cubes. The same procedure is applied to pairs of first differences to derive second differences. When the process is repeated for the second differences, one finds that the third difference is constant and equal to six. This information makes it possible to generate the rest of the table of cubes by reversing the differencing procedure. For example, adding six to the second difference (18) gives the new second difference (24); adding this to the first difference (37) yields the new first difference (61). Finally, adding this to the last cubed number (64) gives the next number in the sequence, 125 or 5^3. The procedure can be repeated indefinitely to generate as many terms as desired using only repeated additions.

The method of differences can be applied to any of the mathematical functions known as polynomials, which have the generic form $y = a_n x^n + a_{n-1} x^{n-1} + \ldots + a_1 x + a_0$. The nth difference of an nth-order polynomial will always be a constant that can form the basis for the method of differences. Polynomials are used to represent many relations in physics and engineering. They can also be used to approximate other functions, such as logarithms and trigonometric functions. In Babbage's difference engines, each column of figure wheels represents the position of one multidigit number in the table. Difference Engine No. 2 can tabulate 7th-order polynomials to 31 figures of accuracy, an impressive accomplishment even by modern standards.



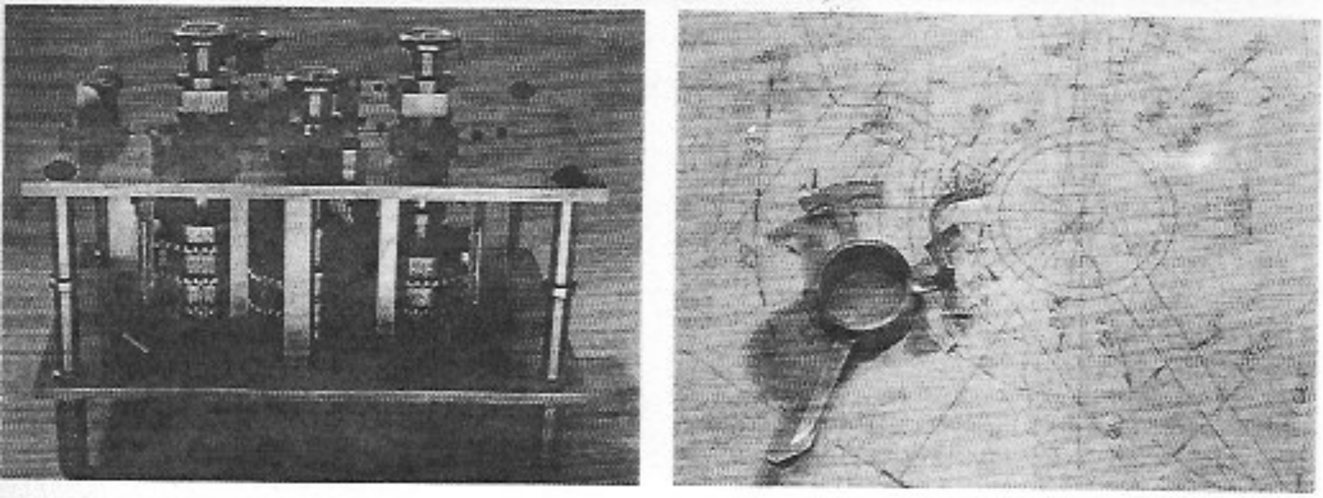
To build Difference Engine No. 2 and to estimate the cost of manufacturing it, we needed full-dimension drawings of its parts. Late in 1989 we contracted a specialist engineering company to produce a set of drawings using Babbage's original set as the authoritative source. Missing information—detailed dimensions, choice of materials, tolerances, methods of manufacture and a great deal of fine detail—had to be supplied.

Dimensions for the individual parts were obtained by measuring and scaling the original plans. The engineering company produced 50 new drawings that fully specified each of the engine's 4,000 parts. Surviving mechanical assemblies show that Babbage constructed his parts from bronze, cast iron and steel. Bromley and Michael Wright of the Science Museum offered advice regarding which material to use for each part. Our colleagues at the Imperial College of Science and Technology analyzed the composition of the components of Difference Engine No. 1 to guide us in selecting an appropriate modern bronze.

No attempt was made to use period machinery in the manufacture of parts. The engine's 4,000 components embody only about 1,000 different part designs, so there is a high degree of repetition. We unashamedly relied on modern manufacturing techniques to produce the many identical parts. We also welded parts that Babbage would have forged. But we scrupulously ensured that Babbage could have produced components of the same precision, though possibly by other means.

Specifying the precision with which parts should be made proved less problematic than we first feared. Bromley and Wright had measured parts from Difference Engine No. 1 and found that Clement achieved repeatability of 1.5 to 2.0 thousandths of an inch, belying the popular belief that mid-19th century mechanical engineering lacked the precision necessary for building Babbage's devices. We adopted a modern engineering standard, confident that it was within the limits of what 19th-century craftsmen could achieve. The process of producing the 50 modern mechanical drawings took about six months and was substantially complete by January 1990.

We were determined to secure a fixed-price contract for manufacture and assembly so as not to repeat Babbage's sorry tale of open-ended expense. After some hard negotiation, the Science Museum and the specialist company



ENGINEERING CHALLENGES were solved in the course of building Difference Engine No. 2. Engineers at the Science Museum constructed a part of the calculating mechanism (*left*) in 1989 to verify the design of the engine's basic adding element. They also built 210 intricate bronze levers (*right, shown atop a design drawing*) for the carriage mechanism.

agreed to a price and to a set of provisions to cushion against unforeseen technical difficulties. The Science Museum committed to underwrite the costs against pledges from a group of five sponsoring computer companies: ICL, Hewlett Packard, Rank Xerox, Siemens Nixdorf and Unisys.

Then, in June 1990, just as the final contract was about to be signed, the company involved went bankrupt after 35 years in business. Reg Crick and Barrie Holloway, the two engineers on the Babbage project, were fired on Thursday, June 7. Unless orders were placed with contractors by close of business the following day, we would incur cost penalties and have to embark on another round of financial negotiation, which would have jeopardized our goal of completing the project in time for the Babbage bicentenary. Officials at the Science Museum interviewed Crick and Holloway on the morning of June 8; by lunchtime they were museum employees. We spent the day frantically writing out part orders for subcontractors and drafting contract terms. At 5:30 P.M., I sprinted to the post office to mail the drawings and orders to the component manufacturers. We made the deadline by minutes.

Difference Engine No. 2 was built in public view in the Science Museum. Fitting and assembly commenced in November and was completed in May 1991. The engine became the centerpiece in the exhibition *Making the Difference: Charles Babbage and the Birth of the Computer*, which opened on June 27, 1991. Even then, the project kept us on tenterhooks. The three-ton Difference Engine No. 2 had not yet performed a full calculation, and it kept jamming unaccountably. We developed debugging techniques to track the source of the jams and continued to work on the machine during the exhibition. On November 29, 1991, less than a month before Babbage's 200th birthday, the machine completed its first full-scale successful calculation. It produced the first 100 values in the table of powers of seven and has functioned without error ever since. The engine ended up costing just under £300,000 ($500,000).

Our project illuminated several aspects of Babbage's skills as a designer and engineer. Historians of technology have debated whether the high standards of precision that Babbage demanded were necessary or were the product of misguided perfectionism. Some researchers have pointed out that cruder engines had been built to good effect. Georg and Edvard Scheutz, a Swedish father-and-son team who were inspired by an account of Babbage's work, built three difference engines, mostly of their own design. The first of these, completed in 1843, had a wood frame and was made using simple hand tools and a primitive lathe. Despite its comparatively rough construction, the Scheutzes' machine performed successfully before the Swedish Royal Academy.

Babbage's difference engines were larger and more sophisticated than those attempted by the Scheutzes, however. Our experiences constructing Difference Engine No. 2 underscored the importance of exacting standards. We had expected that repeat parts made using computer-controlled machines would be sufficiently identical to be interchangeable. This proved not to be the case. Fine tweaking of components to tolerances of no more than a few thousandths of an inch proved necessary, especially for the proper operation of the carry mechanism. Babbage's insistence on high precision was evidently based on sound engineering judgment.

Constructing Difference Engine No. 2 revealed subtleties and ingenuity in Babbage's design not immediately evident in the drawings. The project also gave us tremendous respect for Babbage's ability to visualize the operation of complex mechanisms without the aid of physical models. We hope to extend our explorations of Babbage's elegant designs; to do so, we are currently trying to attract sponsorship to build the printer. In the meantime, we marvel at the physical realization of plans that Babbage drew up nearly 150 years ago. Difference Engine No. 2 stands as a splendid piece of engineering sculpture, a monument to the rigorous logic of its inventor.

FURTHER READING

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