The Construction of Charles Babbage's Difference Engine No. 2

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Charles Babbage designed Difference Engine No. 2 between 1846 and 1848. Contemporary drawings illustrate a machine—never built during his lifetime—that calculates and tabulates polynomials, printing results in hard copy and producing stereotype molds for plates intended for use in conventional printing presses. This article describes construction of the first complete physical realization of a full Babbage engine design and outlines Babbage's ambitions for this advanced engine.

The failed attempt to construct Difference Engine No. 1 is perhaps the best known of the many recounted episodes in Charles Babbage's life. Practical attempts to build the machine were abandoned in March 1833 when, after a decade of design and development, Joseph Clement, Babbage's engineer, downed tools and fired several of his workers employed on Babbage's project following a dispute over compensation.[1] While accounts of Difference Engine No. 1 and its fate have tended to dominate the literature, it is the Analytical Engine, conceived by 1834, to which Babbage largely owes his reputation as the "first computer pioneer."[2] His later difference engine, Difference Engine No. 2, designed after the main work on the Analytical Engine was complete, usually gets no more than passing mention. The history of the three machines, however, is intimately connected.

Origins of Difference Engine No. 2

During the dispute with Clement, Babbage was forcibly distanced from the nuts and bolts of mechanical construction. Deprived of his drawings and engine parts, he revisited some of his early ideas on calculating engines. Using the "beautiful fragment"—a small section of the engine assembled by Clement in 1832—as a physical aid and with drawings back in his possession in July 1834, Babbage made the essential transition from calculation to computation—from the mechanized arithmetic of the Difference Engine to programmable general-purpose computation the principles of which he embodied in the designs for the Analytical Engine.[3]

The designs for the Analytical Engine incorporate most of the essential logical features commonly found in a present-day general-purpose digital computer.[4] These include programmability (Babbage used punched cards), an internal repertoire of automatically executable arithmetical functions (direct multiplication, division, addition, and subtraction) and a range of system and circuit functions including microprogramming, pipelining, iteration or looping, conditional branching, and parallel processing. A further feature of the design is the engine's internal architecture that separates the "memory" he from the "processor." Using descriptions borrowed from the textile industry, Babbage called the memory "the store," and the processor "the mill." The separation of store and mill foreshadowed von Neumann's scheme that has dominated computer architectures in the electronic era. The designs do not feature facilities for internally storing programs: Instruction sequences as well as data were held externally on fanfold, pasteboard punched cards and input from mechanical card readers.

It is important to note that Babbage nowhere used the terminology invoked here to describe logical features. The use of terms such as program, microprogram, pipelining, iterative looping, conditional branching, and processing is a backward projection from the modern computer age and is fraught with the known historiographic hazards of anachronical interpretation—views of the past that do not take account of the alteration of perceptions with time.

In 1846, with the major work on the Analytical Engine design done, Babbage began to design a new machine, Difference Engine No. 2[5] (see the sidebar, "Babbage's Difference Engine No. 2: Overview," for additional information). Though concerted work on the new engine dates from 1847, there is evidence that Babbage had been actively mindful of the

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Babbage's Difference Engine No. 2: Overview

Difference Engine No. 2 was designed between 1846 and 1848. The built machine weighs 5 metric tons and consists of 8,000 parts equally divided between the printing and stereotyping apparatus, and the calculating section (see Figure 5 in the main text). The side view of the machine (Figure 4 in the main text) is one of the main drawings in the original set of 20, and one that is most evocative of its overall shape. The drawing shows a machine 11 feet long and 7 feet high with the depth varying between 18 inches and 4 feet. The three main sections of the machine are the control mechanism alongside the crank handle on the right, the calculating section consisting of eight vertical column assemblies located in the central rectangle, and the printing and stereotyping apparatus, on the left.

The engine is operated by turning the crank handle. The handle drives, via bevel gears, a set of cams arranged in a vertical stack. There are 14 pairs of conjugate cams—that is, each of 14 cams has a companion cam the profile of which is a geometric inversion of its mate. This paired arrangement provides positive bidirectional drive: Shafts and columns are lifted and positively driven downward rather than relying on gravity. The 28 cams control the lifting, turning, and sliding motions required to execute the repeated additions for the method of finite differences. The crank handle also drives the printer and stereotype apparatus from a long shaft that runs the length of the underside of the machine and which is driven by a large bevel gear on the underside of the cam stack.

Numbers are stored and operated on using figure wheels engraved with the decimal numbers zero through nine (Figure A). Each digit value in a multidigit number is represented by a separate figure wheel. Negative values are represented by complements. Numbers are stored and operated on in columns of figure wheels with units at the bottom, tens next above, hundreds next above, and so on.

The machine has eight columns, or axes, each with 31 figure wheels, one column for each of seven differences, and a column for the tabular result. The tabular value appears on the leftmost figure wheel column in Figure 4 in the main text, the first difference column is next and so on. The seventh difference column is on the extreme right.

The engine automatically calculates and tabulates any seventh-order polynomial to 31 decimal places using the method of finite differences, prints the result to 30 places on a paper roll, and impresses the same results on soft material to produce stereotype molds from which printing plates can be made. Initial values are set by hand from a precalculated table by rotating the figure wheels after disabling the security mechanisms.

Typically, when finite differences are used as a manual technique, one adds the higher order difference to the next lower order difference in a fixed series of separate additions. Mapped onto the engine, this requires adding the constant difference on the seventh difference column to the sixth difference column, the sixth difference to the fifth difference, and so on. However, instead of stepwise repeated serial addition of this kind, Babbage split the addition cycle into two. During the first half-cycle, the values on the odd difference columns are added to the adjacent even difference columns, and in the second half-cycle the even differences are added to the odd differences. Provided the initial setup values are offset appropriately, this pipelining arrangement has the same effect as adding differences in a sequence of seven separate additions. The advantage of the half-cycle arrangement is a shortened calculating cycle, more efficient use of hardware, and a fixed cycle time that is independent of the number of differences.[1]

For a seventh-order polynomial, the machine executes seven 31-digit decimal additions each calculating cycle to produce each next value in the table. Each new tabular value is automatically transferred to the output apparatus for printing and stereotyping. For polynomials of order less than seven, the higher-order difference columns are set to zero and play no part. The engine, eased through use, produces one result every six seconds.

References and notes

1. D. Swade, *Charles Babbage's Difference Engine No. 2: Technical Description*, Science Museum Papers in the History of Technology, Science Museum, 1996, pp. 66-67.

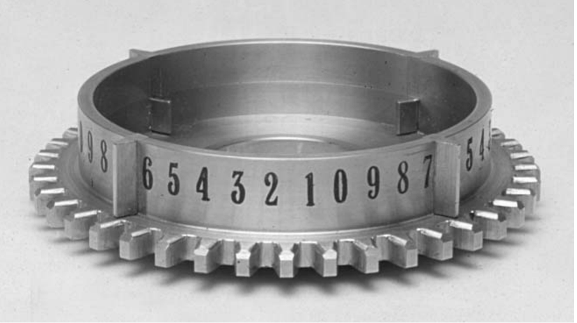

Figure A. Figure wheel. One of 248 similar wheels. The outer nibs warn the tens carriage mechanism. If a figure wheel exceeds 9, a carry is required to the next decade. As the wheel passes from 9 through to 0, the outer nib latches a device that warns that a carry is still required. (Photo courtesy of the Science Museum, London.)

Difference Engine during the design of the Analytical Engine. A drawing dating from as early as March 1842, for example, shows an improved version of the successive carriage mechanism first used in Difference Engine No. 1.[6] The timing of Babbage's preoccupation with a new difference engine is confirmed by his later recollection:

> About twenty years after I had commenced the first Difference Engine, and after the greater part of these drawings had been completed, I found that almost every contrivance in it had been superseded by new and more simple mechanism, which the construction of the Analytical Engine had rendered necessary.[7]

Babbage was consistent in his portrayal of the Analytical Engine's influence on an improved difference engine design. In 1864 he again recalled:

> … in labouring to perfect this Analytical Machine of greater power and wider range of computation, I have discovered the means of simplifying and expediting the mechanical process of the first Difference Engine.[8]

As a design challenge, the functions of the Analytical Engine were vastly more demanding than those for the earlier machine. The mechanisms for direct multiplication and division, for example, required intricacy and complexity well beyond those for the repeated additions in the Difference Engine.

Babbage's near obsession with minimizing the execution time of all arithmetical functions led him to devise more-efficient techniques for simple addition, not least to make room in the timing cycle for multiplication and division that were irreducibly more time-consuming, relying as they did on sequences of repeated operations. The anticipating carriage mechanism, for example—which was devised as a time-saving improvement to the mechanism used in the earlier Difference Engine—he extravagantly ranked as "the most important part of the Analytical Engine."[9] The technique allowed all the tens carries in a number to be executed at the same time, rather than serially as in his earlier design. The anticipating carriage mechanism is one example of many in which the demands of the Analytical Engine raised Babbage's design capabilities to new levels of sophistication, economy, and elegance. Though he did not use the anticipating carriage technique in Difference Engine No. 2, Babbage is explicit about the influence on its design of his work on the Analytical Engine. He wrote that, for his new difference engine, he "proposed to take advantage of all the improvements and simplifications which years of unwearied study had produced for the Analytical Engine."[10] This was no false claim. Difference Engine No. 2 uses roughly three times fewer parts (8,000 compared to 25,000) for a similar calculating capacity.

There is a further direct and intimate connection between Difference Engine No. 2 and the Analytical Engine: The two machines share the same plans for the stereotyping apparatus.[11]

The designs for Difference Engine No. 2 were offered to the government in 1852 in a letter to the prime minister, Lord Derby. In offering an improved machine, it seems that Babbage was concerned to discharge some residual discomfort at the failure to complete Difference Engine No. 1. Babbage wrote:

> I feel, in laying this representation before your Lordship, and in making the offer I now make, that I have discharged to the utmost limit every implied obligation I originally contracted with the country.[12]

The offer to the government was rebuffed, and Babbage retreated yet again into a series of bitter grievances. No attempt was made to construct the machine in Babbage's lifetime. The plans remained on the drawing board for 140 years—until metal was first cut for an experimental trial piece in December 1986.[13]

Sources and interpretation

The set of drawings for Difference Engine No. 2 consists of 20 main views, several derivative tracings, and technical descriptions expressed in Babbage's Mechanical Notation—an elaborate idiosyncratic system of signs and symbols that served as an abstract descriptive language he developed as a design aid.[14] The drawings and notations make no concessions to anyone seeking to understand the machine from scratch. Apart from the drawings and notations there is practically no introductory material, guiding explanation, textual description, or clues to the logic or rationale for the designs. The material cited represents a free-standing source from which his intentions had to be decoded.

The drawings for Difference Engine No. 2 are the most complete set that Babbage produced. There is no evidence that any are missing, and since no attempt was made to construct the machine, the set of drawings was never split up for the execution of separate tasks or exposed to the hazards of dirt and damage in a workshop environment. They were also spared the revisions and improvements to which Babbage subjected most of his other designs, often leaving the machines imperfectly specified or in transitional states of incompleteness. It seems that, for once, Babbage was content to leave well enough alone.

The original drawings and notations represent the principal contemporary data source for the construction of the machine. However, the small team at the Science Museum was fortunate not to have to start from scratch in its attempts to understand the functions of the mechanisms. Bromley, Australian computer scientist and historian, had, as Visiting Research Fellow, studied the technical archive of Babbage's drawings held in the Science Museum Library, London, during a series of short sabbaticals from the University of Sydney starting in 1979. As part of a larger analysis of Babbage's calculating engines, Bromley had decoded the drawings for Difference Engine No. 2, arrived at an understanding of the overall design, general layout and operation of the machine's basic elements, and produced a short draft summary for an unpublished book chapter that described the machine's essential features.[15] At that time, Bromley's paper was the only written description of the engine.[16] It was the authority of Bromley's detailed work on this and other of Babbage's engine designs, and his conviction that the drawings represented the design of a viable working machine, that gave credibility to the undertaking to construct it.

The original sources are sufficiently detailed to describe the shape and nominal size of individual parts, their physical interrelationship, and, through interpretation, their intended function. However, for all their richness, the drawings are not sufficiently detailed to serve as a specification for manufacture: No information is provided as to choice of materials, methods of manufacture, order of assembly, lubrication, precision, or finish.

The drawings are deficient in other respects. There are dimensioning inconsistencies where the same parts are shown differently sized in different views; layout errors; and there are incompletenesses in the design (omitting any detail for driving the inking rollers, or for advancing the stereotype trays, for example).[17] As well as instances of omitted mechanisms, there are redundant assemblies. For example, a complete carriage axis is shown for the highest difference column (the seventh difference), which, being the last, performs no function at all: Once set with an initial value, none of the associated figure wheels can exceed 10 in ordinary operation. The drawings contain other errors, one of which (in the mechanism for the carriage of tens) is fatal to the correct operation of the engine.

Although this litany of deficiencies sounds damning, none of them compromises the validity of the basic logic, design principles, or intended function of the machine. Babbage made no attempt to construct the engine, and the deficiencies in the specification for the most part represent the gap between an advanced design—arrested in an incomplete state of engineering development—and a working machine. The gap, in short, is one of engineering completeness rather than of logical or operational principle.

The trial piece

The proposal to construct Difference Engine No. 2 was made by Bromley in May 1985 during one of his sabbatical visits from Sydney. I had recently been appointed curator of computing at the Science Museum, and Bromley appeared on my doorstep to introduce himself to the new incumbent.

The timing of Bromley's arrival was uncanny. Part of my curatorial responsibilities included care of the defining set of surviving mechanical assemblies of Babbage's machines. I was aware that almost every published account of Babbage's efforts attributed his failure to the limitations of 19th-century mechanical engineering. I was both perplexed and incredulous that, with advances in manufacturing, no one had attempted to realize any of his designs once the supposed limitations of his time had been removed. Nagging historical questions had troubled Babbage scholars—did the complex circumstances of Babbage's failures mask the technical or logical impossibility of his machines? Had the machine been built, would it have worked? Was Babbage an impractical dreamer or a designer of the highest caliber? Here was Bromley, with an ambitious scheme that might advance the debate. Part of the motivational landscape was a serious historical agenda.

Bromley explained in a covering letter to Dame Margaret Weston, director of the Science Museum, that he was convinced from his studies that the drawings represented a viable design for a working machine, and that building a working engine would have historical value beyond simply proving the viability of this particular design. He wrote that

> Construction of the Difference Engine No. 2 would not only confirm the soundness of Babbage's logical and mechanical design principles in this case but would also lend conviction to the entire range of his designs for automatic computing engines.[18]

The proposal concluded with the suggestion that the complete engine would memorialize Babbage as the first pioneer of the computer. He wrote

> The completed Difference Engine No. 2 would stand as a tribute to the forefather of the modern

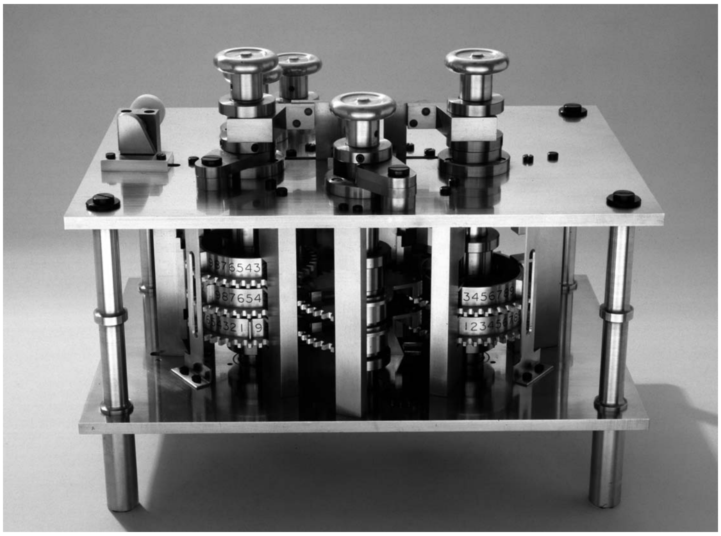

Figure 1. Trial piece, 1989. Adds a two-digit decimal number to a three-digit number and takes account of the tens carriage. (Photo courtesy of the Science Museum, London.)

> computer and one of the most ingenious mechanicians of the nineteenth century. It should be finished in time for the 200th anniversary of Babbage's birth on 26 December 1991.[18]

The proposal made no mention of funding, management, or manufacturing capacity.

The upshot of the proposal was approval to construct a small section of the engine as a test piece. The trial piece was a critical staging post in the construction of the engine.[19] It would allow verification of the basic arithmetical mechanism and exploration of a variety of technical concerns. I was also aware of the strategic value of a working trial piece to promote the project and as a fund-raising aid.

The trial piece added a two-digit number to a three-digit number with the result correct to three digits. The full engine is automatic in that the lifting and turning motions necessary for the repeated additions are executed automatically by an internal control system driven by turning the crank handle. The trial piece did not have the benefit of this complex drive mechanism. Instead, it was operated manually: The dozen or so separate operations involved in the nondestructive addition of two numbers were executed by manually lifting and turning knobs, catches, and sliders in the prescribed sequence to add, restore, and carry, and also to perform the locking operations that secured the mechanism from derangement at different points in the cycle (see Figure 1).

The original timetable allowed for one year to complete the trial piece. Ultimately, for cumulatively mundane reasons, it took four. The trial piece had a false start. The designs prepared hastily during a short visit from Bromley in January 1986 were incomplete at the time of his return to Sydney to meet university commitments. Though Bromley had spotted the design error in the original drawings, in the rushed circumstances of January 1986 he had not attempted a solution.

In July 1987, the project was joined part time by Peter Turvey, a member of the curatorial staff in the museum's engineering department, and a weekend marine engineering hobbyist. His brief was to coordinate the production of the trial piece.

After a desultory attempt by the Science Museum's workshops to use the incomplete drawings, this first attempt was scrapped in October 1987. For the second attempt, I contracted out the design drawings to Rhoden Partners Ltd., a small UK engineering design company that had, in the 1950s, been commissioned to produce replicas of Babbage's engines for IBM, and now specialized in designing and building one-off prototypes for the manufacturing industry. Rhoden was conveniently situated in Acton, West London, a few miles away from the Science Museum. The first meeting with Rhoden took place in January 1988. We were starting from scratch two years after the start of the first attempt.

Reg Crick was the Rhoden engineer assigned to the project. Crick, close to 60 at the time, was a seasoned mechanical design engineer. He had philosophically survived the professional insecurities of life in engineering design—the sudden scrapping of projects, the financial vicissitudes of companies in engineering development, and the roughhouse of commercial imperatives. He was modest and methodical, with an inventive flair more often associated with more overtly volatile temperaments. Crick played a critically important role in the construction project. The team I now had consisted of Crick, Turvey (part time), and, when needed, occasional remote consultation by telex to Bromley, 11,000 miles away in Australia.

As mentioned, there is a flaw in the carriage mechanism as depicted by Babbage. Figure 2 shows the layout of the cluster of axes around each figure wheel column. The layout is right-handed and is the same for both the odd and even difference columns as is clearly indicated in several plan views. As drawn, there is a conflict between two functions: If the figure wheels rotate in the correct direction to add, then the associated warning mechanism for the carriage of tens fouls and jams. The principle of the mechanism is valid, but the layout as depicted in the drawings is unworkable. Bromley had spotted the problem in his original analysis and had offered several solutions.[15]

The solution we chose as the one most likely to have been adopted by Babbage was to make a mirror image of the carriage mechanism for alternate axes. Crick found that using opposite-handed parts had unforeseen consequences: The new arrangement involved small but critical alterations to the angular positioning of end stops and locks, and this adjustment would have to be carried through the whole specification for each of the eight axes. The new arrangement also involved a reversal of the direction of rotation for certain circular motions.

New fully specified drawings for the trial piece were available in March 1988; the mirrored configuration used in the trial piece, and adopted in the full engine, is shown in Figure 3. Testing the mirror configuration became the main purpose of the trial piece. Issues of clearances, tolerances, wear and tear, gear tooth profile, choice of materials, and torque that had so preoccupied us took a back seat.

The trial piece was built in the Science Museum workshops and completed in February 1989, three years behind schedule. Exquisitely made, bright, shiny, and elegantly complex, it was an immediate hit (see Figure 1). It attracted media coverage and, as we hoped, impressed trustees and sponsors. The trial piece proved conclusively that the modifications to implement the mirror-imaged solution to the design flaw worked and would serve as a sound technique on which to base the full construction. It also served as a pedagogic aid to demonstrate the essential arithmetical function. What was unexpected was the role it played in visualizing the working of the machine during the design and the preparation of full drawings.

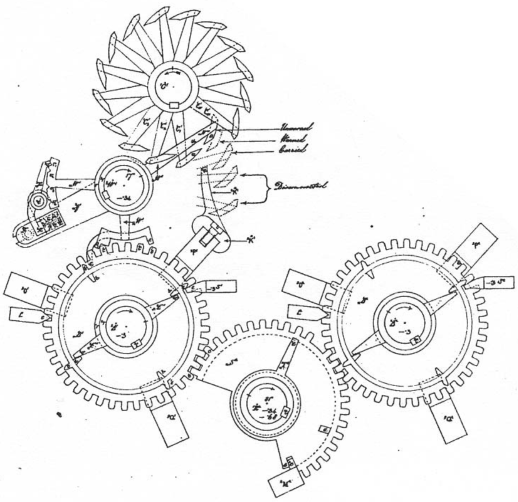

Figure 2. Design drawing. Addition and carriage mechanism (Science Museum Library Babbage Papers, drawing BAB [A] 171 part, "Difference Engine No. 2. Addition Carriage and mode of Driving the Axes," undated). This original layout by Babbage has a design flaw. (Drawing courtesy of the Science Museum, London.)

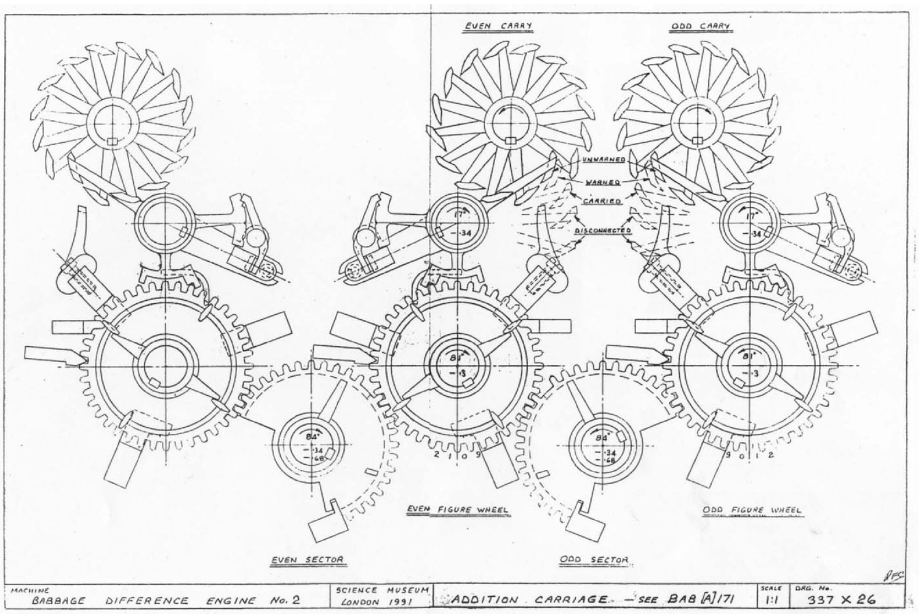

Figure 3. Design drawing. Addition and carriage mechanism with mirror-imaged solution to the design flaw, 1991. (Drawing courtesy of the Science Museum, London.)

Authenticity

The flaw in the layout of the carriage mechanism was the most significant and potentially damaging of the errors we identified. Modifying the design in any way at all presented a basic curatorial dilemma and raised the fundamental question of authenticity. If the engine was built as drawn, then we had no expectation that it would work. The final object, if achieved, would be an intriguing piece of Victorian sculpture but one that would prove nothing about the essential viability of Babbage's schemes. If, on the other hand, the original designs were modified, in what sense could a working engine claim to be a vindication of Babbage's work?

The way out of the impasse was the realization that it was a mistake to view Babbage's design as sacrosanct and unimpeachably perfect. Building the engine was not the slavish physical implementation of an abstract ideal with doom attending even the smallest deviation from the master's instructions. The project was more in the nature of a resumption of a practical engineering project that had been arrested in 1848. Had Babbage proceeded from design to manufacture, the deficiencies in the drawings would have become evident. There would have been no way of avoiding them, and he would have sought solutions. We were simply picking up where he left off, and the task for us was to find solutions with conscientious regard for contemporary practice while using the best knowledge available of Babbage's style of working. We approached each new need with the question, What would Babbage have done? and proceeded to seek historically sensitive solutions.

The issue of authenticity was a central concern. I was determined that nothing would compromise the value of the construction in drawing historically meaningful conclusions about Babbage's world. We would need to be able to robustly resist the charge that "Yes, you built the engine, but Babbage could not have." Credible defense against this charge provided the ruling principle for all issues of authenticity. For each design modification, we first sought solutions that Babbage had used elsewhere in his designs; we only resorted to fresh thinking once this quest was exhausted. A second principle was that of reversibility, that is, to incorporate the facility for demounting any added assembly or modification so as to restore the machine to the state depicted by Babbage in the original drawings.

The manufacture of parts for the full machine was beyond the capacity of the Science Museum's in-house workshops and was contracted out. Further, the manufacturing and build costs were beyond anything the Science Museum could reasonably fund from its ever-diminishing Grant-in-Aid from the government. Sponsorship was the only solution. We needed fully detailed piece part drawings for fixed-price quotes to fix the sponsorship target. In November 1988, the Science Museum approved funds for the Rhoden engineering designers to estimate the cost and timescale for producing fully detailed drawings, tooling, and materials for a complete machine. At this stage we downscaled our expectations and abandoned the prospect of building the printing and stereotyping apparatus for the bicentennial deadline. I judged that the cost of building the printer would put the sponsorship target out of reach, and we were already several years behind schedule.

Producing detailed specifications raised production issues—choice of materials, methods of manufacture, precision, finish, typography for engraving, and lubrication—all issues that went well beyond those addressed in the manufacture of the small trial piece. To help resolve historical issues of this kind, the project had the benefit of Michael Wright, the Science Museum's curator of mechanical engineering. Wright's knowledge of 19th-century workshop practice is encyclopedic. The history of tools and workshops is his profession, his vocation, and his private passion. Stepping into his private workshop with its period treadle lathes, oil-stained wooden benches, leather drive belts, and work in progress is to step into the world of Babbage and Clement.

Tolerancing and the interchangeability of parts were critical issues. One of the features of the engine designs is the repetition of near identical parts. Babbage did not have available to him production techniques that offered inherent repeatability—stamping and pressure die-casting, for example—and parts were made one at a time by a combination of machining and hand fitting. The understanding between the designer and the machinist, whether specified explicitly on a drawing or not, was that a part would be made to fit—that is, trimmed and tweaked by hand at the discretion of the machinist until it functioned correctly.

Babbage designed the engine at a time when manufacturing was in transition between craft and mass production techniques and methods for manufacturing repeated parts were still incipient. Until the 1850s there was practically no standardization in manufacturing. Each workshop had its own lathes, often custom built, and the master screw from which screw threads were cut usually differed from lathe to lathe even in the same workshop. The notion of a tolerance, the interval within which the dimension of a part will fall, is an anachronism—a backward projection from a later age.

With 4,000 parts to make, we abandoned any wistful notions of recreating a period workshop and building the engine using contemporary 19th-century tools and practices. There was simply no time. We unashamedly used modern techniques including computer-controlled manufacture. But no part was made more precisely than was achievable by Babbage himself, although possibly by other means. Wright and Bromley, friends and colleagues before the engine project began, had taken measurements from parts of Difference Engine No. 1 and established that Clement was able to make repeated parts within a tolerance of two-thousandths of an inch. This became the taboo threshold: An absolute condition was that repeated parts would be made to tolerances no finer than this.

The choice of materials for the construction was resolved through expert advice and inspection of the relics of Babbage's partial assemblies. These studies indicated that the use of gunmetal, cast iron, and steel was consistent with the period. Gunmetal, a form of bronze, was in common use in Babbage's day. What we did not know was whether Babbage would have tweaked the mix of copper, tin, and zinc by the addition of other elements such as lead and phosphorous to achieve particular properties of durability, workability, brittleness, and sliding friction. No one on hand seemed to know much about the state of metallurgical knowledge in the 1840s. To resolve the issue we prevailed on the Department of Materials, Imperial College, to analyze the composition of loose parts left over from Babbage's earlier works that were in the Museum's collection. X-ray microanalysis showed that the mix was within an acceptable and recognizable standard, and a close modern match was found.[20] Although we now had clear ideas on what materials Babbage would have used, the original drawings left us in the dark about what materials would be used for which part.

In January 1990, I assembled an advisory team and convened a series of blockbuster meetings. Bromley happened to be in London en route to Greece to work on the Antikythera mechanism, the oldest known geared instrument, and was able to join the group. The posse of curators, historians, and engineers consisted of Crick, Bromley, Wright, Turvey, and me. The five of us met for four full days of marathon consultations sustained only by tea, coffee, and an occasional gobbled sandwich. The work was grueling and painstaking, and the level of detail oppressive. We went through the drawings for the 4,000 parts and, for each, debated the material, method of manufacture, visual and functional authenticity, finish, and did a final check on precision. By the end of the last meeting, on 17 January 1990, Crick had enough information to complete the drawings.

Run-up to the build

With historical issues of specification resolved, Crick translated Babbage's 20 main views into 100 new working drawings that fully detailed each of the 4,000 parts of the calculating section of the engine drawn to conform to modern manufacturing conventions. By now Crick had the most detailed understanding of the workings, engineering design, and manufacturing issues of Babbage's engine. He designed and drew up the omitted mechanisms, and each went through a curatorial approval system. For the few instances in which we were unable to resolve technical issues from the original drawings, I turned, as a last resort, to the notations. Traditional drawing boards and drafting pencils were used: The production of the new drawings was unaided by CAD technology.

Barrie Holloway, a Rhoden engineer, managed the independent three-party tender process required by government procurement policy. Each of three companies quoted for all 4,000 parts, and Holloway undertook the complex process of splitting the order to mix and match the most economic combinations of supply. The permutations were nightmarish. The final figures were available in May 1990. The cost had gone up from an estimated £201,000 to £246,000. No one was surprised.

With drawings complete, funding secure, fixed price quotations in hand, 18 months until the deadline, and Rhoden Partners on tap, it looked as though we were in with a chance. But without warning, Rhoden went bust. The situation was rescued by prevailing on the Science Museum to hire Crick and Holloway immediately. My own role until then had been that of project director, project and contracts manager, curator with responsibilities for technical interpretation and authenticity, technical adjudicator of design options, fundraiser, and publicist. I would now also have direct line management for Crick and Holloway and directly manage the build through to completion including the subcontracted manufacture of parts to companies specializing in various processes—milling, pattern making, casting, gear cutting, spring winding, case hardening, and so on. Crick and Holloway showed up for work at the Science Museum on a fixed-term contract on Friday, 8 June 1990, three days after they had been fired.

The build

The engine was assembled in full public view on a prime site on the ground floor of the Science Museum. An enclosure was built around the machine (known as the pen) in which Crick and Holloway, white-coated, slowly assembled the machine. The pen included two workbenches with engineer's vises and basic hand tools for filing, drilling, reaming, fit-

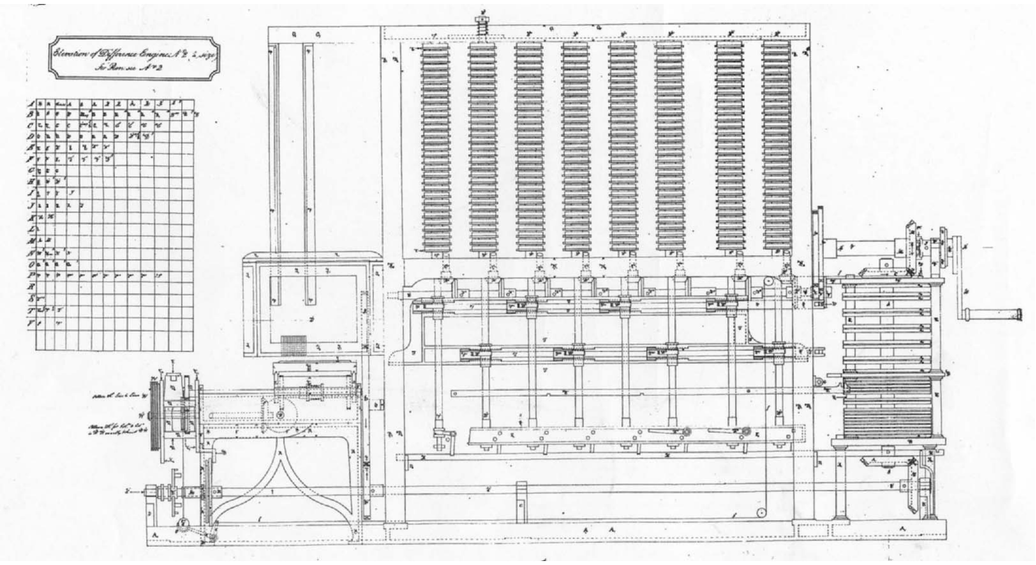

Figure 4. Design drawing. Main elevation showing crank handle (right), calculating section (center), and output apparatus (left). Science Museum Library Babbage Papers, drawing BAB [A] 163, "Elevation for Difference Engine No. 2." (Drawing courtesy of the Science Museum, London.)

ting, and finishing. These processes were undertaken in open view. Parts requiring machining were taken to engineering workshops in the museum's basement or returned to the suppliers for modification.

The 4,000 parts were made in six months by a total of 46 separate specialist subcontractors. The first deliveries arrived from the contractors in September 1990, and the 4,000 parts were supplied in batches over the next six months.

The strategy for the build was not to assemble the machine in its entirety and then test it in one dramatic episode.[21] This may have been theatrical but ran against proven engineering practice. The machine was, after all, a prototype. There were too many unknowns. Instead, the engine was assembled in small stages, and each stage tested before we proceeded to the next. Initially, progress was tentative and exploratory. The heavy framing pieces that define the engine's outline were assembled first, and then, at the crank handle end, the 28 cams that generate and orchestrate the sliding, lifting, and turning motions required for repeated addition were stacked. The drive trains for lifting and turning the columns followed next. These trains, located below the eight sets of vertical axes, consist of sets of racks and pinions for the circular motions, and of bell cranks driven by long links for the vertical motions (see Figure 4). Finally, the eight figure-wheel columns, the sector wheel columns, and carriage axes were progressively installed starting from the crank handle through to the tabular value at the opposite end (the sidebar, "Babbage's Difference Engine No. 2: Overview," explains the relationship between the columns and the differences).

In January 1991, with the cam stack and some of the cam followers assembled, the first attempt was made to turn the handle. As a precaution against unyielding loads, a four-to-one reduction gear had been inserted into the manual drive to ease the operator's task. Despite this, after a small rotation, the crank handle would not budge. Analysis showed that the rise on the cams that controlled the locking action was too steep to allow rotation, and the cam follower, which is intended to follow the profile of the cam, could not mount what presented itself as a triangular obstruction and a shock load that could not be overcome.[22] The timing cycle was too crowded to allow us to ease the angle to provide a gentler ramp.

Elsewhere in the engine, Babbage had solved the problem of excessive loads by the use of counterbalancing springs. The heaviest load is that presented by the columns of figure wheels, sector wheels, and their vertical shafts that need to be lifted and lowered during each calculating cycle. Babbage provided strong springs at the top of each vertical shaft. The springs, which are in compression, support the columns in their resting position. A single example of this, with implied duplication, is shown at the top of the engine on the first difference column (the second column from the left) in Figure 4. Instead of having to lift, via the drive mechanism, the full weight of the columns, all that is required

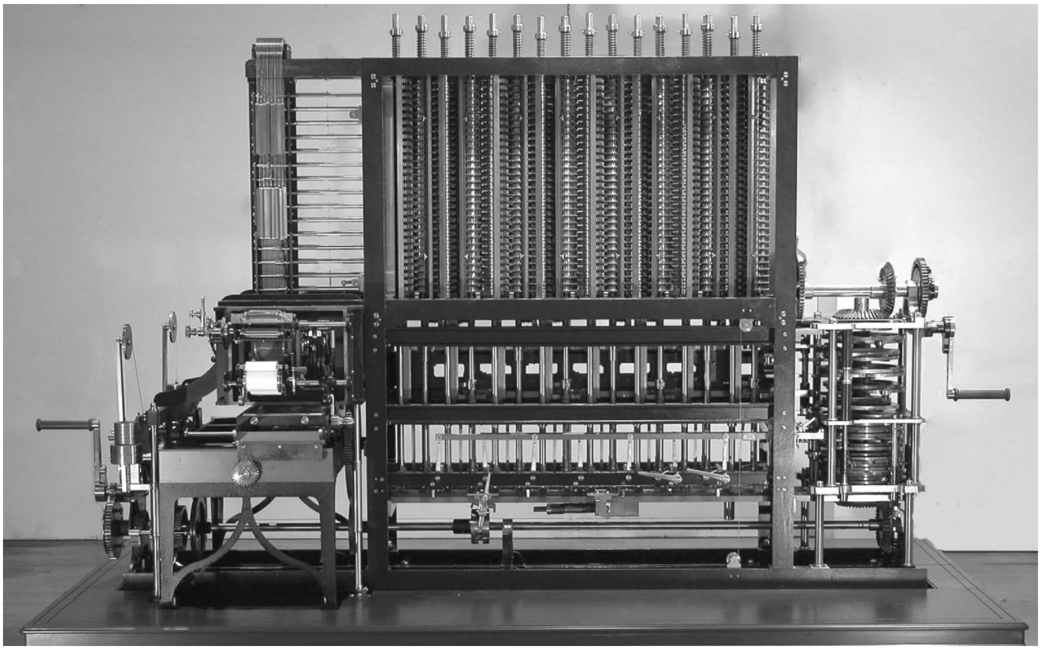

Figure 5. Difference Engine No. 2, on display at the Science Museum, 2005. Eleven feet long and 7 feet high, the engine weighs 5 metric tons and has 8,000 parts. Main crank handle is at the right; the calculating section is in the center; and the output apparatus (printer and stereotype mechanisms) are at the left. (Photo courtesy of the author.)

is a nudge up or down from the equilibrium position. The forces for these deflections are small compared to the forces required to lift and lower the full weight of the assemblies, and the exertions of the operator are correspondingly relieved. Using this technique as a model, Crick devised a mechanism using a strong counterbalancing spring to relieve the load. The mechanism was fixed under the lowest framing piece, out of sight for normal viewing (see Figure 5).

The phasing of internal actions is critical. The calculating cycle is crowded with little margin for deviation from strict synchrony. If a part moves fractionally late or early, the mechanism is likely to seize or break as it fouls a mating part. When parts were first positioned on the machine, they were rarely in their correct orientation. Each had to be adjusted and then fixed permanently. The drawings simply show all gears and rotating parts permanently pinned to their shafts already in their correct and final positions. There is no indication of how the correct positions are to be determined before pinning. Hundreds of parts were fitted one at a time by trial and error using grubscrews for incremental adjustment for each trial. Until all the parts were correctly phased, the machine would jam incessantly. Breakages, especially of the brittle bronze carry levers, which are the most fragile part of the carriage mechanism, were not uncommon, especially as the reduction gear in the drive reduced sensitivity to obstructions.

Jamming is an intended feature of error detection built in by Babbage. The engine is a decimal digital machine. It uses the familiar Arabic number system, and it is digital in the sense that only discrete integers are legitimate representations of digit values. So the value represented by a toothed figure wheel at rest in an intermediate position between two digit-values is indeterminate, and the occurrence of this state signals that the integrity of the calculation has been compromised.

What makes Babbage's designs digital is not any inherent discreteness in the motions of the basic logical element (a gear wheel) but the locking and control mechanisms. The most common method used for "digitizing" the motions occurs in the form of a wedge that is driven between teeth of the gears at various points in the cycle. The wedge has three functions:

- Locking. When inserted between two teeth, the wedge locks the wheel and prevents derangement except during specific predetermined windows in the timing cycle. The wedges, which run like sword blades up the columns and act on all 31 figure wheels at the same time, are called locks (see Figure 2).

- Self-correction. Because of its angled profile, the insertion of the wedge has a self-correcting action: Small deviations from exactly discrete increments are corrected by the centering action of the wedge. This action is analogous to electronic pulse shaping.[23]
- Error detection. The wedge acts as an error detector: If a toothed figure wheel has deranged by more than half the gap between teeth (2-1/4 degrees), then the tooth blocks the entry of the lock and causes a jam.[24] The crank handle seizes, and the operator is alerted that the calculation has been compromised.

The locking mechanisms, unique to Babbage's designs, are intended to ensure the calculation's absolute integrity. Babbage used a variety of security mechanisms, one of which is a device of extraordinary subtlety, the function of which was not fully understood until it was assembled and operated. The device in question involved horn-like attachments in the carriage mechanism (see Figure 2). In accordance with Babbage's intentions, these were carried through to the new drawings, although their function was not fully evident at the time. In live operation, it became clear that the horns are a security measure that prevents the figure wheels from deranging while waiting for a possible carry from below. The device prevents the wheel from incrementing unless driven from the legitimate source at a particular point in the cycle. Babbage went to great lengths to make good his assertion that his machines break, jam, or operate as intended, that is to say, they would never deceive.[25]

One of the greatest difficulties in the commissioning stages of the engine resulted from the absence of any provision for debugging. When the machine jammed, there was no provision for easily isolating one section from another to help localize the fault. The whole machine, including the printing and stereotype apparatus, is one monolithic "hard wired" unit. Drive gears and levers are pinned to their shafts. Drive rods and links are shown in the original drawings as pinned or riveted and therefore difficult to dismantle once assembled. In the event of a jam, all one could do was poke around with a screwdriver, or in extreme cases a crow bar, prying here and there for some give or play that would indicate that the jam occurred earlier in the machine. The hunt-and-peck technique was repeated until a moving part was found with no play, and the first occurrence of this was inspected as the possible source of the jam. During assembly and commissioning, the machine jammed countless times each day. When the machine was locked solidly, the starting point for fault detection was haphazard and demoralizing.

Our first attempt to set up the machine to perform its first calculation took place on 23 June 1991, four days before the exhibition opening. In anticipation, I had calculated the initial setting up values for a table of powers of seven, the first test calculation we would try, using a CP/M version of a Microsoft spreadsheet, package, Multiplan, running on a North Star Horizon computer I had bought back in the US in 1979. I also produced a printout of the first 80 values of the function $y = x^7$ the first test calculation we would try. In the first trial we found that the setup procedure described by Babbage was self-corrupting. The odd and even axes are set up at different parts of the cycle, and advancing the machine to the second setup point deranged the settings already made. The solution was simple enough: to provide temporary locks (vertical metal strips with slotted fixing holes) that could be slid in and out and fixed in the engaged or unengaged position using knurled nuts. The self-corrupting sequence is an illustration of the earlier assertion that although the deficiencies in the original design were many and varied, none were issues of basic logic that compromised Babbage's original intentions—that is, modifications were issues of engineering implementation rather than of principle.

Fitting and assembly started in September 1990, and the calculating section was fully assembled by late June 1991. At the time the machine went on exhibition on 27 June 1991, it was still plagued by jams. At the gala opening, the engine was demonstrated to international media with all figure wheels set to zero. This prevented jams and allowed the visually arresting spectacle of the rotating helices of the carriage mechanism to be shown. The sight of the rippling helices distracted the press from the historically inconclusive state of progress, and media coverage was uniformly positive.

Commissioning and debugging continued in the intervals between twice-daily public demonstrations but without the protection of our enclosed pen. The sources of the jams were progressively eliminated, and, with use, the initial stiffness began to ease. The path to reliable working was a gradual process of eliminating more refined forms of minor fault.

The final adjustments were to some of the carriage mechanisms. Babbage had insisted on the highest precision achievable at the time as a uniform standard. Michael Lindgren, for one, has argued that the lessons of the Scheutz difference engines, the first of which was finished in 1843, are that such precision was not only unnecessary but that the consequent costs and delays contributed to Babbage's failure.[26] We had thought that by using computer-controlled manufacture, repeated parts, would be sufficiently similar to be interchangeable. This proved not to be the case. The most delicate parts are the bronze carry levers which, because of their intricacy, were made in two parts soldered together in a jig. We found that some 10 percent of the 210 carry levers required final adjustment by hand (through trial and error) using a specially made tool to bend the arms.

The engine performed its first full automatic error-free tabulation of the function $y = x^7$ on 29 November 1991, 27 days before Babbage's 200th birthday. Though the final adjustments were finicky, the machine, once pinned and adjusted, has been, from the time of its first correct calculation, robustly and persistently reliable. Almost without exception, calculation errors have been traced to an earlier human setup or operational error.

Each new tabular result requires seven 31-digit decimal additions. At first the engine calculated at a rate of one result (seven 31-digit additions) every 10 seconds. As the machine eased with use, the rate speeded up to one result every 6 seconds.

Output apparatus—Funding and preparation

The automatic production of a machine-replicable record of results is an integral part of the conception of the engine. The output apparatus that prints and stereotypes results is described in the original set of drawings to the same level of detail as the calculating section. The operation of this compound output apparatus is described in the sidebar, "Difference Engine No. 2: Printing and Stereotyping."

The unique circumstances of the bicentenary provided a hard deadline as well as leverage to raise sponsorship through the benefit by association with a high-profile project. This had now passed. There was now no deadline and no public event on the back of which to attract corporate support.

The funding breakthrough came, indirectly, through Bill Gates. The European press launch of his book *The Road Ahead* was held in the Science Museum on 3 December 1995, and the photo opportunity was to be the spectacle of Gates turning the engine's handle. When he arrived at the museum, I gave Gates preliminary guidance on the turning technique while a rabid pack of some 40 paparazzi, corralled into a small area behind the engine, shouted his name to pop a shot as Gates turned in reflex to the caller. The atmosphere was aggressive and threatening, and Gates appeared discomfited by the assault. The confusion and noise of the situation prevented me from making a pitch, but a member of Gates's party, Jonathan Lazarus, trailed behind and was interested in a source of Enigma machines. I took his card and we exchanged emails, in one of which I asked what Gates had thought of the machine. Lazarus relayed to me that Gates had thought that the "machine was 'very cool' and that he had been pleased to see it."

I sought Lazarus's advice about any potential interest Gates or Microsoft might have in sponsoring the printer construction and emailed a project description. He referred me to Nathan Myhrvold, group vice president of applications and content, at Microsoft. What followed was a year-long email courtship with Myhrvold, aided by a visit and a demonstration, on 13 March 1997, of the completed section of the machine. He followed up shortly after with a proposal to personally fund the construction of two printers and another engine. The first printer would complete the Science Museum's existing machine; the second printer–engine pair would be a replica of the whole engine for display, and occasional use, in Myhrvold's house in Seattle. When I told Reg Crick, the now-retired engineer who had played a key role in constructing the calculating section, all he said, with what I hope was an audible smile, was "What took you so long?"

Orders for parts were dispatched in October 1998. Crick came out of retirement and assembly work in the gallery started late in 1999. Assembling Babbage's machines is a two-person task, and Holloway had long since left. I had a young, well-qualified in-house conservator–machinist and engineering workshop enthusiast, Richard Horton, assigned to Crick for the build. He was to be Crick's "apprentice" and was being groomed for the future.

Building the printing and stereotype apparatus

The output apparatus was built in public view directly onto the already completed calculating section of the engine. Building the apparatus was substantially more difficult, troublesome, and frustrating than building the calculating section. We originally estimated that it would take a year to assemble. It took well over double this time. The single biggest

Difference Engine No. 2: Printing and Stereotyping

A central feature of Babbage's calculating engine designs is the automatic capture of machine-replicable output. Difference Engine No. 2 features an output apparatus that automatically typesets, prints, and stereotypes results. The apparatus is shown on the left-hand side of Figure 4 in the main text. The upper section contains the print wheels, inking apparatus, and paper roll for hardcopy, as well as the stereotype wheel punches. The lower section is a movable platform that positions the stereotyping trays under the stereotype punches for each new result. The whole apparatus, which is bolted to the main framing, consists of some 4,000 parts and weighs and estimated 2.5 metric tons. As an ensemble, the two units produce one-off inked hardcopy results to 30 digits on a print roll as well as a stereotype mold for the production of printing plates for use in a conventional printing press. Figure B shows a plan view.

The printing and stereotyping apparatus is directly coupled to the calculating section, and each new 30-digit tabular value is transferred automatically from the results column, via a system of racks, pinions, and spindles, to the print wheels. The tabular result is transferred at the same time to two sets of punches for stereotyping (see Figures C and D). Typesetting is automatic, and each result is printed and stereotyped during the calculating cycle in which it is generated: There is no buffering or storage of the result and there is no time overhead to print—that is, printing and stereotyping is accommodated in the calculating cycle and takes no additional time. Each cycle leaves an inked impression of a 30-digit result on the paper print roll that advances automatically to provide fresh paper for each line (see Figure 7 in the main text and Figure E). This hardcopy printout is intended as a record and checking copy only; the operator cannot alter the line spacing and format. The production of multiple copies for distribution is achieved through stereotyping.

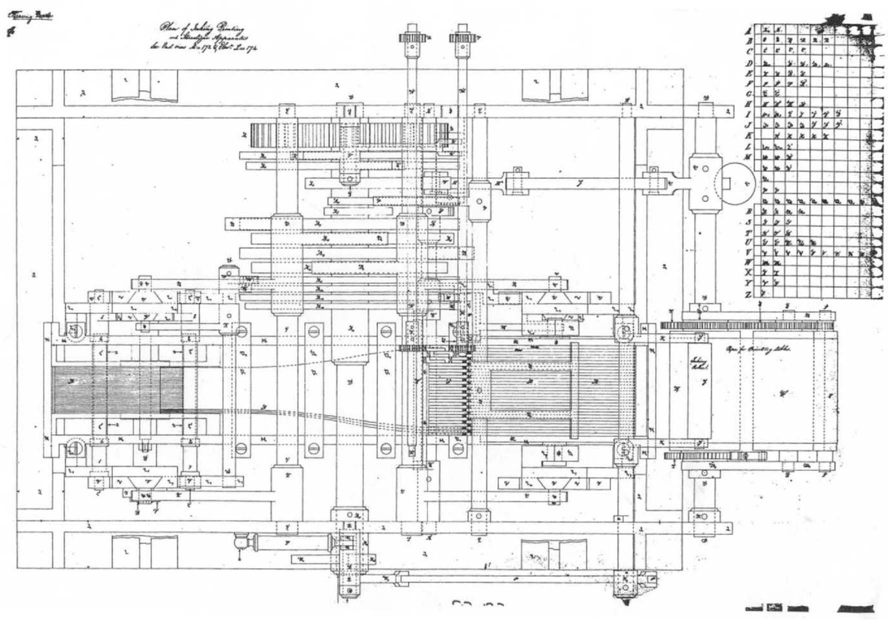

Figure B. Plan of output apparatus. Science Museum Library Babbage Papers, drawing BAB [A] 173, "Plan of Inking Printing & Stereotype Apparatus," undated. (Drawing courtesy of the Science Museum, London.)

There are two sets of stereotype punches, one with a larger, and one with a smaller font. Each set consists of 30 wheels, one for each digit of the result, with hardened steel number punches fixed at the circumference (see Figure D). The wheels making up the punches have 2 degrees of freedom only: rotational (to register each digit of the result), and ver-

difference between the two sections of the machine is that, although there is a large number of repeated parts and assemblies in the calculating section, there is very little repetition in the output apparatus. The learning curve throughout the fitting and assembly stayed relatively flat.

Like the calculating section, Babbage drew the output apparatus as a single monolithic "hard wired" assembly with no provision for adjustments. Unlike the calculating section, the output apparatus is dense and deep with poor access to its internal workings. Any small adjustment or fitting required lifting out the whole 2.5 metric ton assembly to enable access. Each trial-and-error adjustment meant countless separate cycles of removal and refixing. A large overhead gantry was mounted permanently to lift out the apparatus, sometimes several times a day.

Inevitably, there were modifications to the

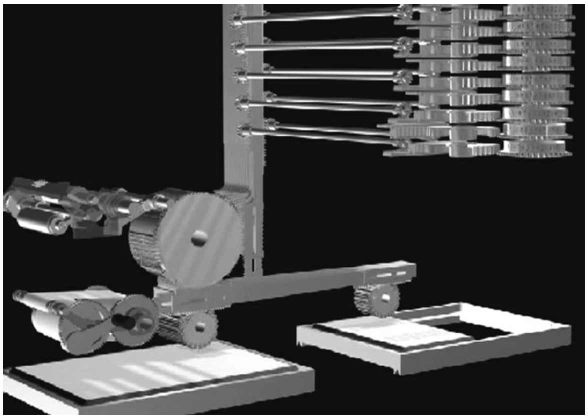

Figure C. Output apparatus (computer simulation) showing figure wheels (top right), printing apparatus (left), and stereotyping punches and trays (bottom). (Photo courtesy of the Science Museum, London.)

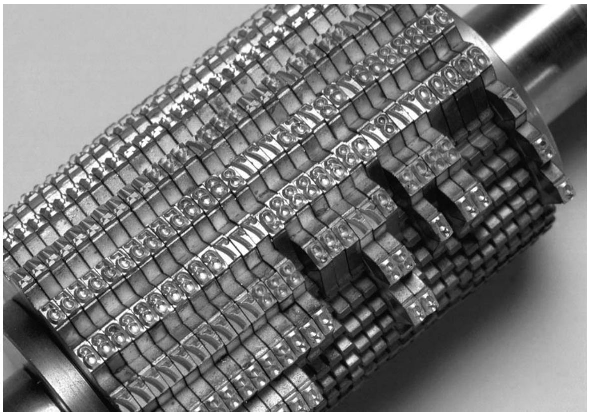

Figure D. Stereotyping wheel punches for large font. (Photo courtesy of the Science Museum, London.)

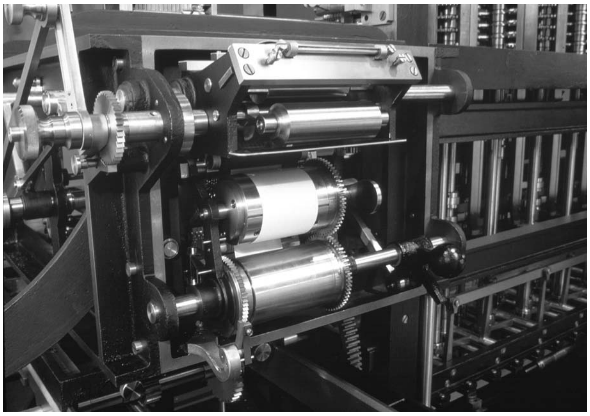

Figure E. Printing mechanism showing inking rollers and ink bath (top), and paper drums in raised position taking an inked impression from the print wheels. (Photo courtesy of the Science Museum, London.)

tical (lowering to impress the result, and raising to return to receive the next result). The wheel punches are assembled on the same shaft and are lowered and raised together as a set. Below each set of punches is a bronze tray to take the soft material to receive the impression (see Figure C).

During each calculating cycle, the punches are driven downward into the trays below, and the material is impressed with all 30 digits at the same time in one action. After each impression, the tray advances automatically and repositions itself to receive the next result on a new line or column and the distance between the impressions (the line height) is determined by the incremental advance of the tray. The smaller tray advances by a proportionately smaller amount to give a reduced line height in keeping with the smaller font size. The platform or carriage supporting the stereotype trays has 2 horizontal degrees of freedom, which allow the trays to advance down the page (line to line) or across the page (column to column). The carriage is driven by falling weights that are rewound automatically at the end of a column or page. The layout of results can be programmed by the operator by selecting from a menu of pattern wheels, which control the incremental behavior of the moving platform. Programmable formatting features include line height, number of columns, margin widths, number of lines on a page, blank lines between groups of lines, and the ability to have results progress line to line with automatic column wrap, or column to column with automatic line wrap.

A feedback mechanism from the output apparatus to the calculating section automatically halts the machine at the end of a stereotyped page to prevent an overrun. This ensures that the first new result on the fresh tray is the next result in the sequence and that no results are lost in the changeover.

designs. Some were precautionary. Others were in response to problems that arose during commissioning. Precautionary measures included the provision of counterbalancing weights to relieve the deadweight of the 30 vertical racks forming part of the drive train that transfers the tabular value from the last column to the print wheels. Another precaution was the provision of robust support brackets and legs to relieve the load on the bolts that fix the whole apparatus to the engine frame. Such measures were reversible and unproblematic.

Some modifications were introduced in response to operational difficulties during commissioning. There is, for example, no way of uncoupling the drive to the output apparatus from the calculating section: The drive is provided by a single unbroken shaft that runs the full length of the underside of the engine and is directly driven by a large bevel gear under the

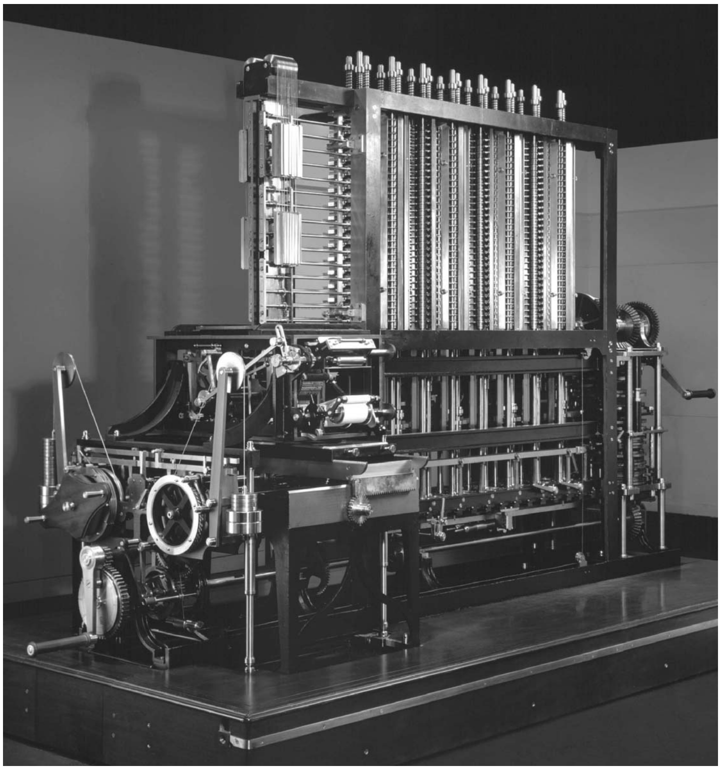

Figure 6. Difference Engine No. 2, 2002. Foreground: Printing and stereotyping apparatus. Rear: Calculating section and drive. (Photo courtesy of the Science Museum, London.

cam stack (see Figure 4). So to run the printer, you need to run the engine. This is not practical either during commissioning and testing, or when using the machine for tabulation. With no provision for uncoupling, working on the output apparatus required two people, one at the crank handle, the other at the output end 11 feet away. This, too, was impractical: Countless adjustments, visual inspections, and tests requiring incremental operation would be inconvenient or impossible to perform with two operators, one unsighted, stranded at the crank end. There was also the frequent need to work on the two units separately, and debugging was easier if the units could be uncoupled.

A more serious problem would arise when using the machine for tabulation. In some situations, the output apparatus needs to be cycled without disturbing the engine. Priming the inking rollers by cycling the printing system is one such need. Advancing the stereotype trays so that they can be removed, refilled, or replaced is another. Both these operations may be required during a calculation run. However, without the facility for uncoupling, the only way to cycle the output apparatus was to cycle the engine, and doing so alters its internal state and destroys the continuity of the calculation run.

The solution was to sever the main drive shaft to the output apparatus and insert a clutch that could couple or break the drive as needed. Crick designed the clutch with manual interlocks so that the drive can be recoupled if and only if the output apparatus and the calculating section are correctly phased. A crank handle, a duplicate of the handle specified by Babbage, was provided at the printer end so that the output apparatus could be driven directly without affecting the calculation section. (See the left-hand side of Figures 5 and 6).

One intriguing additional device was a "bounce catcher." An inking roller swings downward each calculating cycle to ink the printing wheels immediately before an impression is taken. At the end of the return swing, it was found to rebound from its end stop and foul the paper roller, which was in the upward swing of its trajectory. With the timing cycle too tight to separate the actions, Crick designed a mechanism to trap the roller in its home position on the return swing. In preventing unwanted oscillations the action of the mechanism is not unlike that—by way of electronic analogy—of a Schmidt trigger, which latches the output in a fixed state when a noisy input signal passes through a reference threshold.

The biggest single difficulty that bedeviled getting the output apparatus operational was friction in the drive trains that transfer the results from the calculating section and the output apparatus. The main source of this was sliding friction between 30 vertical racks. The racks slide against each other, and we found that surface tension using any form of oil created surprisingly high resistance to sliding. We tried various forms of wet and dry lubrication without success. A combination of relieving the contact surfaces by milling selected shapes in the faces of the racks, skimming down the overall width, and using dry graphite lubrication ultimately solved the problem. The stiffness in the train hampered progress almost until the end and masked several other faults in the process.

One fundamental design issue threatened to undermine Babbage's ambitions for the output apparatus. The output apparatus automatically typesets the printed and stereotyped results. In doing so, the mechanism aligns the appropriate digits on the printing wheels and stereotype wheel punches for each result. As described earlier, in the calculating section Babbage used wedge-shaped locks, which have a centering action that helps to ensure fully digital operation. The same locking mechanism is used in several places in the output apparatus. The question that remained unanswered until last was whether the action of the wedge-shaped locks would be sufficient to align the stereotyping punches accurately enough—that is, to the analog standards of exactness for a typographically acceptable result.

The first clue that the wedge-shaped locking system might not be adequate was the imperfect alignment of the experimental inked paper-roll hardcopy output (see Figure 7). Examination revealed that the forces with which the locks operated were not sufficient to align the stereotype punches, and this had been masked by the stiffness in the vertical racks. Crick devised a collapsed link mechanism that drove one of the existing locks home with sufficient force to align the punches to an acceptable standard.

The various intended features of the output apparatus were exercised for the first time in March 2002. Although refinements to the inking apparatus were made subsequently, this date marks the completion of the machine, as originally designed.

The project to construct the engine started with Bromley's proposal in May 1985. It took just under 17 years to realize an operational machine.

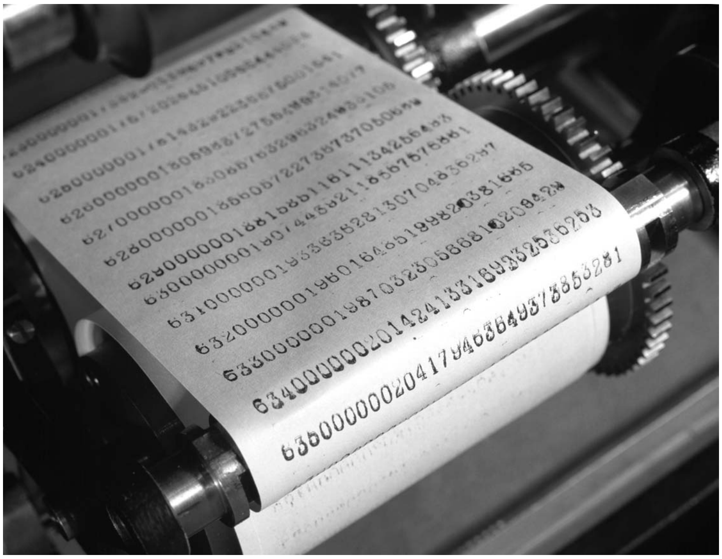

Figure 7. Experimental printout of a seventh-order polynomial. The argument is the left-hand three columns. (Photo courtesy of the Science Museum, London.)

Lessons

It is legitimate to ask what was learned from this project, and what was learned that could not otherwise be learned. The machine was built to tolerances achievable by Babbage, using materials available to him, and introducing reversible modifications to the design using solutions used by Babbage elsewhere. Despite many modifications, no flaws were found that compromised the design's essential logic or principles. Given that the machine works, and was built with conscientious attention to issues of authenticity, the project provided definitive answers to some of the earlier historical questions about Babbage's standing. It is fair to conclude that had Babbage built the machine, it would have worked. Second, the fact of its working vindicates Babbage as a designer of extraordinary practical inventiveness, this in addition to the already recognized intellectual accomplishments of his designs for computing engines. So we can demonstrably say that Babbage was not an impractical dreamer but a designer of the highest caliber. These assertions could not be made with the same conviction without the empirical confirmation of a working machine.

There were lessons learned that in principle could have been learned without the construction, but were not. The subtle device for locking the figure wheels during the carriage cycle was not fully understood until built and operated. Another contingent finding was the maximum speed of operation and the limiting factor determining this. We found, after the mechanisms had eased with use, that the maximum speed of the machine as designed was 10 results per minute.[27] Also, the limiting consideration was a gear that gets thrown out of mesh, and this is probably remediable by a stronger spring.

In principle, one could have analyzed, inferred, and foreseen these and other features. But nobody did. Like playing chess, there is a limit to the number of moves one can foresee, and the explosion of uncertainties from more than a few counterfactual conditionals in the train of reasoning soon sabotages confidence in any conclusions one might draw. In some instances, there is no substitute for practice.

Having a physical machine to operate focused attention on issues of operational procedure, and gave us insights into the implications for contemporary table making. One insight was into the possibility of suppressing leading zeros. The construction of the printwheels and stereotype wheel punches indicates that suppressing leading zeros in the printed hardcopy was clearly not intended. Replacing wheel punches with blank spacers is possible but not practical, and it is likely that leading zeros would have been cut or machined off the printing plate after it was cast.

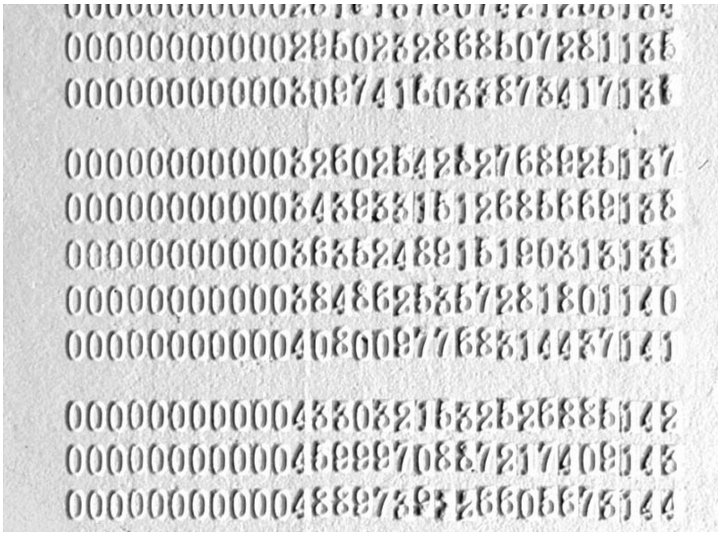

Figure 8. Experimental stereotype mold in plaster of paris. Detail. (Photo courtesy of the Science Museum, London.)

Close contact with the practical procedures for stereotyping gave suggestive insights into issues that had remained puzzling. One such was the question of why Babbage's designs showed engines working to so many digits of precision.[28] Faced with the practical task of stereotyping a run of calculations raised the question of how the argument would be tabulated. If the full 30 digits are used in the printed result, then generating the argument requires a separate run using only one difference to increment each next value. The tabulated argument would then later have to be matched to the separately tabulated results at the stage of making the printing plates.

A feature of the machine is that the calculating section can be split horizontally to isolate upper and lower sections. This is done by disabling the carriage of tens at any digit position on each of the eight columns of figure wheels. The manual adjustment to do this is simple and takes only a moment. Separate calculations can then be carried out in each of the isolated sections with the 30 digits apportioned between the two sections at will. So one section of the machine can perform the tabulation of a polynomial function of up to the seventh order, and a separate section can tabulate the argument using only one difference to progressively increment the argument. The argument and result both occupy the last column of the engine and are automatically printed and stereotyped on the same line alongside each other (see Figures 7 and 8).

Generating the argument and the result in the same calculation run, by distributing the machine's full digit capacity between the argument and result, contributes to the debate about the apparently extravagant digit precision of Babbage's designs: The full digit capacity may not have been intended only for the results.

Conclusion

The successful construction of the engine was instructive in furthering historical understanding of Babbage's capabilities and achievements. Constructing the machine revealed features and subtleties that had not been fully appreciated through analysis of archival sources. Moreover, the fact that the machine works without material modification to the original drawings vindicates Babbage as a designer of the highest caliber. The meaning and value of the machine, both historical and technical, are far from exhausted: the existence of a complete and working Babbage tabulating engine offers an opportunity to further explore automatic tabulation as practiced in the 19th century and to acquire operational know-how inaccessible by nonempirical means.

The physical artifact—large, intricate, and imposing—serves to memorialize Babbage as the great ancestral figure in the history of computing, and in this it achieves the purpose of its construction as articulated by Allan Bromley in 1985. The engine rounds off a historical narrative. The successful construction of the machine closes an anguished chapter in computer pre-history: The Science Museum is a government institution funded from the Treasury, and the original deal between the government and Babbage to fund his machine to completion has finally been fulfilled.

The sumptuous spectacle of the machine in operation is an arresting sight. The act of witnessing the startling choreography of its moving parts and the clanking synchrony of its motion prompt us to experience the promise of a future already past.[29] Objects are interpreted and reinterpreted by successive generations. Others will find other meanings.

Acknowledgments

I would like to acknowledge the Science Museum for providing the context and environment for undertaking the project to construct Babbage's calculating engine. Special thanks to two Science Museum directors in whose tenures this project fell: Margaret Weston, who encouraged and financially supported the late Allan Bromley's pioneering work on Babbage's engine designs, and Neil Cossons, who spiritedly backed the project to construct the engine at critical points in its eventful trajectory, despite the risks. Generous financial support was provided by ICL, Unisys, Hewlett-Packard, Rank Xerox, and Siemens Nixdorf for the construction of the calculating section completed in 1991. Tom Bales, director of Symbiosis Foundation, funded the preparation of the drawings for the printing and stereotyping apparatus. Special thanks to Nathan Myhrvold for generously funding the construction of the printing and stereotype apparatus completed in 2002, as well as a complete replica engine, and for his good-humored patience awaiting the outcome. Most of the illustrations were photographed by David Exton.

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