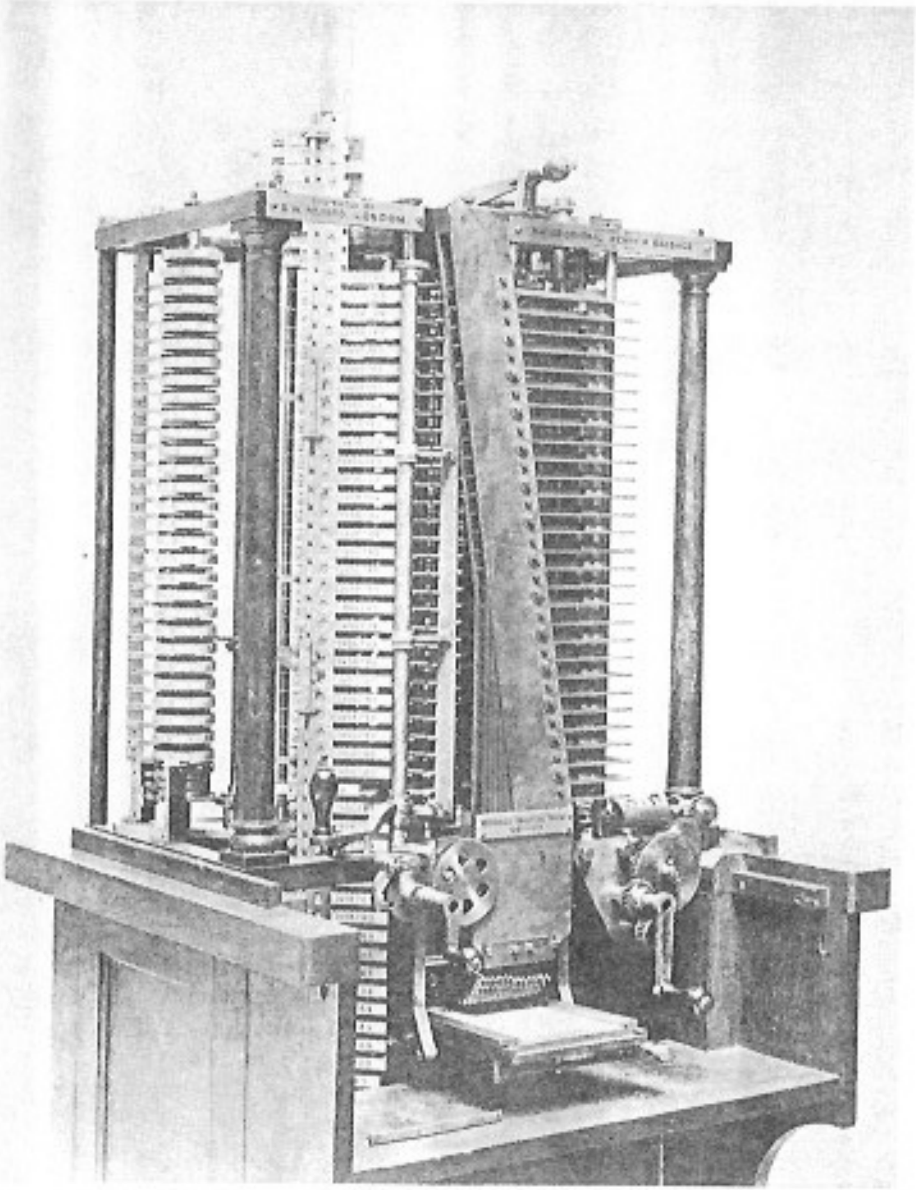

This machine is held in the Science Museum, London S.W. 7. It was made from the drawings of the Analytical Engine left by Charles Babbage and was constructed partly by his son and partly by the firm of R. W. Munro. It is the "mill" and printing mechanism, capable of performing the four arithmetical operations and printing the result to 29 places. Illustration British Crown Copyright, Science Museum, London.

CHARLES BABBAGE AND HIS CALCULATING ENGINES

SELECTED WRITINGS BY CHARLES BABBAGE AND OTHERS

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INTRODUCTION

I

Charles Babbage is a name known fairly widely today; in his own time the value of his work was recognized by few of his contemporaries, and he was held a crackpot by his London neighbors. His name has emerged from obscurity in the past generation because it has become increasingly clear that he was a man far ahead of his time. That knowing and critical figure, J. M. Keynes, his students still recall, admired Babbage highly. Today there are applied mathematicians everywhere who share his passion for developing calculating machines; their technical resources have vastly improved, but the fundamental principles of design remain very similar. The British magazine *Nature* entitled a discussion of one of the first large American calculators "Babbage's Dream Comes True," and described that Harvard relay computer, Mark I, as a realization of Babbage's project in principle, but with the benefit of twentieth-century mechanical engineering and mass production methods for its physical form. A few years ago B. V. Bowden in his excellent book on calculating machines, *Faster than Thought*, said that Babbage enunciated the principles on which all modern computing machines are based. Unquestioned pioneer in the field of large-scale mathematical machines, Babbage was, in a sense, the unheralded prophet of the even newer field now known as operational research, foreshadowed in his book *Economy of Manufactures and Machinery*. This study of scientific manufacturing processes of all kinds, written as a by-product of his interest in mathematical machines, was in fact the only major undertaking he actually completed. He was ahead of his contemporaries in still a third way: he made a determined campaign for Government subsidy of scientific research and education at a time when research was still, to a large extent, a gentleman's hobby.

II. LIFE

Born in Devonshire in 1792, Charles Babbage was the son of a banker who later left him a considerable fortune. Because of poor health, he was privately educated until he entered Trinity College at Cambridge in 1810. He was already passionately fond of mathematics before coming to college and was discouraged to find then that he knew more than his tutor. He soon had a great circle of friends, or rather, a number of circles—chess- and whist-playing groups, fellow members of the Ghost Club, and boating companions, all in addition to mathematical colleagues. Of the latter, his most intimate friends were the younger Herschel (later Sir John) and George Peacock (later Dean of Ely). The three undergraduates entered into a compact that they would "do their best to leave the world wiser than they found it." In 1812, as their first step toward the achievement of this goal, the three, together with several others, founded the Analytical Society, hired rooms for it, read mathematical papers, even published transactions. Babbage, Herschel, and Peacock translated Lacroix's *Differential and Integral Calculus* and published two volumes of examples (see page 24). In spite of considerable opposition, the Society fought valiantly to put "English mathematicians on an equal basis with their Continental rivals," and actually had a profound effect on the future development of English mathematics. Babbage believed that he was certain to be beaten in the tripos examinations by both Herschel and Peacock, and preferring to be first at Peterhouse rather than third at Trinity, he transferred in his third year. In fact, he stood first in Peterhouse in 1814, and received his M.A. in 1817. For about ten years after his graduation he published a variety of mathematical and physical papers, mostly on the calculus of functions, but also including one on Euler's study of the knight's move in chess and one on barometric altitude measurements.

Babbage, Herschel, and Peacock continued to be friends after they left school. Each in his own way lived up to their joint compact, though their careers were very different. Peacock devoted himself to mathematics and astronomy until finally he decided to join the ministry. He took his D.D. in 1839, and shortly thereafter became Dean of Ely, a post he filled with great vigor and success. Herschel, after a brief apprenticeship at law, decided to follow his great father into astronomy. As a crowning achievement, to supplement his father's work on stars of the Northern Hemisphere, Herschel went to the Cape of Good Hope in 1833, and in four years completed his observations of the southern stars. After his triumphant return to England, his main work was compiling his great catalogues of nebulae and stars. He was knighted by the Crown, served as Master of the Mint, and avoided all scientific feuds; his biographers all report that his was a life full of serenity and innocence. In contrast, Babbage published at thirty his "Observations on the Application of Machinery to the Computation of Mathematical Tables," and was received with general acclaim and presented the first award of the Gold Medal ever given by the Astronomical Society—but spent the rest of his life fruitlessly trying to bring his machines to completion. He was led by his broad interests into many byways, from a vigorous campaign against the policies of the Royal Society to the study of ciphers, and from speculative geology to the design of tools for lathes and shapers, but always his work centered on his beloved engines. His career was a long series of disappointments, and to friends who visited him in 1861 he said that he had never had a happy day in his life and spoke "as though he hated mankind in general, Englishmen in particular, and the English government and organ-grinders most of all . . . in truth Mr. Babbage was a mathematical Timon."

Actually Charles Babbage was a most social and gregarious fellow, with a considerable sense of humor, as one can see in his autobiography. Charles Darwin wrote, "I used to call pretty often on Babbage and regularly attended his famous evening parties." Babbage was an enthusiastic conference man, instrumental in founding the Astronomical Society (1820), the British Association for the Advancement of Science (1831), and the Statistical Society of London (1834). Darwin also recalled a brilliant dinner at his brother's house at which even Babbage who "liked to talk" was outdone by Thomas Carlyle; and an Edinburgh professor who was asked to dinner by Babbage reported that "it was with the greatest difficulty that I escaped from him at two in the morning after a most delightful evening." Encouraged to travel for his health, he made many trips to the continent of Europe, and was equally interested in meeting members of the aristocracy, fellow mathematicians, and skilled mechanics. He was a friend of Laplace and of Alexander Humboldt and knew Poisson, Fourier, and Biot. "It is always advantageous," he advised, "for a traveller to carry with him anything of use in science or in art if it is of a portable nature, and still more so if it has also the advantage of novelty." Among his most useful objects of this sort were some gold buttons stamped by steel dies with ruled parallel lines 4/10,000 of an inch apart, produced by a designer of machine tools named Sir John Barton, who was Comptroller of the Mint. The rainbow patterns playing on these small diffraction gratings, which indeed they were, provided a splendid opening gambit in conversations with strangers.

III. MACHINES

BABBAGE's transformation from a cheerful young man into a bitter old one was to a large extent the result of his devotion to his mathematical machines. He has provided us with two versions of the origin of his ideas about machines, but the one written in 1822 seems more plausible than the other, which appeared in his autobiography some forty years later. According to the first story, Herschel brought in some calculations done by computers for the Astronomical Society. In the course of their tedious checking, Herschel and Babbage found a number of errors, and at one point Babbage said "I wish to God these calculations had been executed by steam." "It is quite possible," remarked Herschel. From this chance conversation came the obsession that was to rule Babbage for the rest of his life. The more he thought about it, the more convinced he became that it was possible to make machinery to compute by successive differences and set type for mathematical tables. He set down a rough outline of his first idea, and made a small model consisting of 96 wheels and 24 axes, which he later reduced to 18 wheels and 3 axes. In 1822, in addition to his above-mentioned original note published by the Astronomical Society, he wrote an article "On the Theoretical Principles of the Machinery for Calculating Tables" for *Brewster's Journal of Science*, and a letter on the general subject to the President of the Royal Society, Sir Humphry Davy. In this letter, Babbage pointed out the advantages such a machine would have for the Government in producing the lengthy tables for navigation and astronomy, and proposed to construct a machine on an enlarged scale for the Government's use. There had been machines since the time of Pascal for carrying out single arithmetical operations, but they afforded little saving of time or security against mistakes. The Astronomical Society received Babbage's proposal with the highest enthusiasm, and the Royal Society reported favorably on his project for building what he called a Difference Engine. In an interview held in 1823 between Babbage and the Chancellor of the Exchequer, a rather vague verbal agreement was made whereby the Government would grant funds for the enterprise which was expected to take three years. Work proceeded actively for four years although Babbage was constantly having new ideas about the machine and scrapping all that had been done before.

In 1827 Babbage went abroad for a year on the advice of his physician, and during this period made a study of foreign workshops and factories to supplement his considerable familiarity with British manufacturing processes. He later used this information in his book *Economy of Manufactures and Machinery*, published in 1832, about which we shall have more to say later. While still abroad, he learned that he was to be appointed Lucasian Professor at Cambridge, the chair once held by Isaac Newton. Although he hesitated because of his work on the Difference Engine, he decided to accept and hold the position for a few years. He remarks in his autobiography that this was the only honor he received in his own country. He resigned in 1839 to devote himself completely to his machines, even though during his entire term of office he neither resided at the college nor taught there. His income as Lucasian Professor was between eighty and ninety pounds a year!

Upon returning to London in 1828, Babbage made a new application for funds to the Treasury. The Royal Society again reported favorably, the Duke of Wellington inspected the model, and once more the Government granted liberal funds for the work, and decided to build a fireproof building and workshop on land leased next to his home. In 1833, when arrangements were made for moving the engine and the work to the new shops, Babbage and his excellent engineer Clement reached a crisis. There had for years been differences about the various delays in salary payments and Clement refused to continue work in the new buildings without new and expensive arrangements. At this point Clement abruptly stopped work and dismissed those of his men who were working on the Babbage job. After months of dispute he allowed the drawings and the parts of the engine to be moved to the new building, but he was legal owner of his tools and retained all those tools which had been so laboriously built in his shop at Babbage's and the Government's expense over six or eight years of effort.

Twelve months after work on the Difference Engine had stopped, Babbage thought of an entirely new principle for a machine which would wholly supersede and transcend the Difference Engine. The Analytical Engine, as he called it, would have far more extensive powers, more rapid operation, and yet a simpler mode of construction than his original design. In 1834 Babbage requested an interview with the First Lord of the Treasury to explain his new idea and get an official decision on whether to continue and complete the original Difference Engine, or to suspend work on it until the new idea could be further developed. For eight years he pressed for an answer either from the First Lord of the Treasury or from the Chancellor of the Exchequer, with whom he corresponded at some length. At last he was advised that the Chancellor and the Prime Minister, Sir Robert Peel, concluded that the Government must abandon the project because of the expense involved. The Government had already spent £17,000 and Babbage had contributed a comparable amount from his private fortune. The parts of the machine already completed and the drawings for the whole machine were deposited in the Museum of King's College, London, were shown at the International Exhibition of 1862, and were eventually delivered to the South Kensington Museum, where they are now. The part on exhibit is in working order and has recently been taken apart, thoroughly cleaned, and reassembled so that an exact copy could be made for the International Business Machine Corporation's museum. The copy was built by the firm of R. W. Munro, who built the "mill" for Babbage's son, see frontispiece.

Much embittered by the Government's withdrawal, Babbage turned his attention to the development of the Analytical Engine, and maintained a staff of draftsmen and workmen to work on drawings and experimental machinery for future construction. As always, Babbage would start work on a model and then abandon it in an unfinished state to start work on a new one. In 1848, after working for several years on the Analytical Engine, he decided to make a complete set of drawings for a second Difference Engine, which would include all the improvements and simplifications suggested by his work on the Analytical Engine. He again offered to give the completed drawings and notations to the Government provided they would build it, and again his offer was turned down by the Chancellor of the Exchequer, whom Babbage termed "the Herostratus of Science, [who] if he escape oblivion, will be linked with the destroyer of the Ephesian Temple."

IV. DIFFERENCE ENGINE

In 1834 the *Edinburgh Review* had published an account of the principles of Babbage's Difference Engine. Inspired by this article, a well-to-do Stockholm printer, George Scheutz, undertook to make a machine of his own. With a little belated financial assistance from his own Government and from members of the Swedish Academy, Scheutz and his son Edward completed, after many years of work, a difference engine of their own, which Scheutz brought to England for exhibition in 1854. Somewhat to Scheutz' surprise, Babbage did everything in his power to help, and in a speech before the Royal Society recommended Scheutz and his son for one of the Society's medals. Babbage's own son Henry used the Scheutz machine to demonstrate his father's pet system of "mechanical notation." The Swedish machine won a Gold Medal in Paris in 1855. Babbage and his son had prepared a series of drawings to accompany the machine and explain its operation. The Scheutz machine was bought for $5,000 in 1856 by an American businessman for the Dudley Observatory in Albany, New York, whose first building was to be dedicated that same year. G. W. Hough, first Director of the Dudley Observatory, was certainly a man to appreciate the machine, for he himself developed, with much effort, both a printing barometer and a very early form of recording chronograph for daily use at the Observatory. The Scheutz machine computed four orders of differences and displayed its results by setting type to eight decimal places. An engraving of the machine standing on its four fluted hardwood legs appears as plate 4 of Volume I of the *Annals of the Dudley Observatory*. The machine was used in Albany for many years in computing Ephemerides and various correction tables, and exists today in a private collection in Chicago. In 1863 an exact copy was made for the British Government and used by W. Farr for the computations for the *English Tables of Lifetimes, Annuities, and Premiums* published by the Registrar-General.

Calculating machines were by no means new; they had been devised by such luminaries as Napier, Pascal, and Leibnitz. Their devices were meant to serve as "desk calculators," like the wonderful and ubiquitous machines whirring on so many desks today, or like the humble slide rule. But detailed mechanical realization of the designer's ideas had not yet been skillful enough to make the machines more than mere curiosities in 1830. Babbage had higher ambitions; he planned to make a machine suited for the computation and direct setting-up in type of lengthy mathematical tables. He was greatly concerned about the errors introduced in the processes of printing and publishing tables, and listed and analyzed many repeated errors. He remarked in the first enthusiastic year of his public campaign to see his machine initiated with government aid: "Machinery which will perform . . . common arithmetic . . . will never be of that utility which must arise from an engine which calculated tables."

The Difference Engine was an embodiment in wheels and cranks of the principle of constant differences. The non-mathematical reader may find Babbage's own account in the *Life of a Philosopher* (see pp. 38–51 in accompanying text) entirely clear. We summarize it here more compactly.

Let us actually construct a table of the squares of the successive integers: 1^2, 2^2, 3^2, 4^2, etc. . . ., using exactly the method of the machine. We set up three columns: the first two columns are work columns, and the answers will appear in column C. To begin we have only to specify their three initial entries and a fixed pattern of

$$\begin{array}{ccc} A & B & C \\ & & 1 \\ & 1 & \\ 2\rightarrow & & \\ & \overline{3}\rightarrow & \\ 2\rightarrow & & \overline{4} \\ & \overline{5}\rightarrow & \\ 2\rightarrow & & 9 \\ & \overline{7}\rightarrow & \\ & & \overline{16} \end{array}$$

procedure. From this we can generate the table as far up as we have the patience to go, using the single mathematical operation of addition. The three staggered columns are shown in the above with the pattern of procedure. The three given numbers are a 2 for column A, 1 for B, and 1 for C. The function of the digit 2 in A is to show that we are constructing a table of the second powers, while the first entries for columns B and C simply tell where the table begins. Complete column A by filling in 2's as far down as you like. Now complete column B by adding in the entries from column A again and again as shown by the arrows. Once column B is constructed its values are fed in turn into column C by addition in exactly the same way. The result in column C is automatic and almost painless construction of a table of the squares of integers, made wholly by this very repetitive pattern of simple addition.

More mathematical readers will recognize the procedure in an obvious notation of the difference calculus: $\Delta_n^2 y=2$; $\Delta_1 y=1$; $y_0=1$. This gives the general rule and the specific initial conditions.

All the work here performed consisted of additions (including the carrying of units to the next higher place), storage (or memory) of previous results, and the repeated addition of the column entries in a certain simple and invariable order. In 1822 Babbage made himself a small machine which could do exactly the operation given above, up to five-place numbers. This was the harbinger of Difference Engine No. 1. The frontispiece to the *Life of a Philosopher* (page 2) is a facsimile of a woodcut of a very similar fragment of Difference Engine No. 1 itself, which has been preserved in the Science Museum in London. By the use of toothed wheels on shafts, not much different in principle from the familiar figure wheels of the mileage indicator on an auto speedometer, the Difference Engine can carry out the operations exemplified above. In the present frontispiece, the first table entry is set at the bottom of the column of figure wheels at the right; column B is the central vertical set of wheels, column A the left-hand vertical shaft. Turning the crank once presents a new figure in the table column, the other columns taking their proper values. In the machine as designed, but never constructed, the number indicated in the table column would each time be transmitted through a set of levers and cams to a collection of steel punches, which would then be in position for stamping the number on a copper engraver's plate. The plate was moved with each turn of the mechanism so that the punched number would appear in the proper place on the printed page. Mechanically all this was far from simple. Recall that standardized machine parts, without hand-fitting, were yet a rarity. Clocks, which most closely resembled this type of mechanism, were still principally hand-fitted. Babbage's plans were on a grand scale—one of his most conspicuous failings—and called for no less than twenty-place capacity, up to differences of the sixth order. The variety and number of bolts and nuts, claws, ratchets, cams, links, shafts, and wheels may be imagined! All of these parts were designed with skill and care, with supplementary mechanism intended to minimize wear, prevent improper registration, and so on. Some of the modern practices of instrument design were foreshadowed, and there is no doubt that the technical devices used were superior for their time. The presence of gauges, of a shaper, of a kind of embryonic turret lathe, of die-cast pewter gear wheels and the pressure molds in which they were made, is evidence enough of that. Babbage even studied the action of cutting tools, and rationalized tool-grinding. But perhaps the very care and thoroughness of the design was its greatest weakness, for it was far from completion when the controversy which ended its financial support became the cause of its postponement after years of work. And the rise of Babbage's own interest in a far grander (and still more unrealizable) project at last killed the Difference Engine. Its state at death was most incomplete, but all the drawings, and a considerable number of the tools, gauges, jigs, and a quite respectable amount of development of methods and machinery had been completed. Precise information cannot be found, but a reasonable estimate would seem to show that Babbage's engine would have cost about fifty times what the similar though more modest Swedish version sold for in the fifties. It would have been some two tons of novel brass, steel, and pewter clockwork, made, as nothing before it, to gauged standards.

V. ANALYTICAL ENGINE

WHAT BABBAGE saw after his work with the Difference Engine was a really grand vision. He had early conceived the notion he picturesquely called "the Engine eating its own tail" by which the results of the calculation appearing in the table column might be made to affect the other columns, and thus change the instructions set into the machine. On this insight, and after a striking mathemetical digression into difference functions new to mathematics, and suggested only by the operation of the engine, he built a great program. It was nothing less than a machine capable of carrying out *any* mathematical operation instead of only the simple routine of differences we have inspected. Such a machine would need instructions both by setting in initial numbers, as in the Difference Engine, and also far more generally by literally telling it what operations to carry out, and in what order. Capable of repeated additions, of multiplication which is hardly more than that, and of reversing the procedure for subtraction and division, the arithmetical unit would do these operations upon command. It would work on previously obtained intermediate results, stored in the memory section of the Engine, or upon freshly found numbers. It could use auxiliary functions, logarithms, or similar tabular numbers, of which it would possess its own library. It could make judgments by comparing numbers and then act upon the result of its comparisons —thus proceeding upon lines *not* uniquely specified in advance by the machine's instructions. All this, which forms the backbone of modern computing development, was to be carried out wholly mechanically with not even a simple electrical contact anywhere in the machine, nor, of course, a tube or a relay. The scale, as usual, was grand. The memory was to have a capacity of a thousand numbers of fifty digits—respectable even by today's standards. Of course the speed of today was wanting. The multiplication which takes not a millisecond in the fast electronic giants of today, and some seconds in a punch-card business machine installation, would have taken the Analytical Engine two or three minutes.

This operation depended upon punched cards (see Note on page xxxiii). They were not the fast-shuffled Hollerith cards moving over handy electrical-switch feelers, but cards modeled on the already well-worked-out scheme of the Jacquard loom. Punched holes in these cards would supply the machinery with numerical constants and directions for operation. The cards would be interposed into long lines of linkages within the engine. Whether or not holes came in the right places would determine the passage of feeler wires capable of linking together the notion of "chains" of columns and whole sub-assemblies. Thus, numbers or even arithmetical processes, transfer from column to column, storage, inspection of given columns already in the store, intercomparison of results, and so on—could be told to the machine. All this was done purely mechanically, and the process was elaborately safeguarded against the perils of friction, wear, jamming, and even errors by human attendants who, at the signal of the machine, were to set in cards at programmed points in the process. This is the barest sketch of the machine. Only looking at the visible complications of a modern machine, and translating them into the still self-conscious machinery of more than a century ago, can do justice to the plan. Charles Babbage would be proud to see how completely the logical structure of his Analytical Engine remains visible in today's big electronic computers.

Babbage was too much concerned with the development of his engines to publish any description of them, but in 1840 he was invited to Turin to discuss his Analytical Engine. In the audience was L. F. Menabrea (later a general in Garibaldi's army) who summarized Babbage's ideas in a paper published in 1842 in the *Bibliothèque Universelle de Genève*. This paper was translated into English and extensively annotated by the Countess of Lovelace (daughter of Lord Byron) and published in *Taylor's Scientific Memoirs*. It is reprinted in this volume (page 225). The Countess thoroughly understood and appreciated Babbage's machine, and has provided us with the best contemporary account—an account which even Babbage recognized to be clearer than his own. Miss Byron studied mathematics and, with the encouragement of her mother's various intellectual friends, her interest continued after her marriage. The Countess often visited Babbage's workshop, and listened to his explanations of the structure and use of his Engines. She shared with her husband an interest in horse racing, and with Babbage she tried to develop a system for backing horses; Babbage and the Count apparently stopped in time, but the Countess lost so heavily that she had to pawn her family jewels. Apparently Babbage was willing to try anything once in an effort to raise funds for his Engine. He once designed a tit-tat-toe machine, which he intended to send round the countryside as a travelling exhibit to raise money for his serious machines. The tit-tat-toe machine was designed to recall a splendid eighteenth-century automaton, with the figures of two children, a lamb, and a cock, alternately clapping, crying, bleating, and crowing. Underneath the bric-à-brac was to be the mechanism for a genuinely automatic machine, slow-moving but unbeatable at tit-tat-toe.

Babbage was persuaded to abandon the exhibition of this machine as an unprofitable venture by someone wise in the ways of the theater, who advised him that it was impossible to compete with General Tom Thumb, the reigning favorite of the day.

VI. MATHEMATICAL INTERESTS

ALTHOUGH BABBAGE never strayed very long from his calculating Engines, his tremendous scientific curiosity led him into many byways—some stemming directly from the main line of his machines, and some that were far afield. The machines themselves were, of course, a direct result of Babbage's great interest in mathematical tables, and he was much impressed with the importance of having them easy to read as well as accurate. In 1826, after a vast amount of labor, he published a table of logarithms from 1 to 108,000 in which he paid great attention to the convenience of calculators who would be using the tables. His work was much appreciated by computers both in England and abroad, and several foreign editions were published from his stereotype plates, with translated preface. In the same year he published a short book called *A Comparative View of the Different Institutions for the Assurance of Life*, which was one of the first clear, popular accounts of the theory of life insurance. He was led into this field as a result of his interest in calculating tables of mortality, and his tables were adopted by several German companies from the German edition of his book. In England his life tables were used by life insurance companies until a new set of tables was compiled by the Government in about 1870 on a Difference Engine built especially for the purpose (see page xvii). In 1831, in an effort to determine which was easiest to read, Babbage printed a single copy of his tables of logarithms in 21 volumes on 151 variously colored papers with ten different colors of ink, and also in gold, silver, and copper on vellum and on various thicknesses of paper.

He was constantly calling to the attention of scientific societies and government offices the number and importance of errors in astronomical tables and other calculations. At one of the first meetings of the British Association for the Advancement of Science, Babbage recommended a calculation of tables of all those facts which could be expressed by numbers in the various sciences and arts, which he called "the Constants of Nature and Art." At another BAAS meeting, in remarking on the vital statistics of an Irish parish, he said "to discover those principles which will enable the greatest number of people by their combined exertions to exist in a state of physical comfort and of moral and intellectual happiness is the legitimate object of statistical science."

He even extended his demand for statistical accuracy to poetry; it is said that he sent the following letter to Alfred, Lord Tennyson about a couplet in "The Vision of Sin":

> "Every minute dies a man, / Every minute one is born": I need hardly point out to you that this calculation would tend to keep the sum total of the world's population in a state of perpetual equipoise, whereas it is a well-known fact that the said sum total is constantly on the increase. I would therefore take the liberty of suggesting that in the next edition of your excellent poem the erroneous calculation to which I refer should be corrected as follows: "Every moment dies a man / And one and a sixteenth is born." I may add that the exact figures are 1.167, but something must, of course, be conceded to the laws of metre.

It is a fact that the couplet in all editions up to and including that of 1850 read "Every minute dies a man, / Every minute one is born," while all later editions read "Every moment dies a man, / Every moment one is born."

Like many mathematicians he was fascinated by the art of deciphering, and believed firmly that every cipher could be deciphered with sufficient time, ingenuity, and patience. He began composing a series of dictionaries in which words were arranged according to the number of letters they contained, then alphabetically by the initial letter, then alphabetically by the second letter, etc. This work was never finished, nor were the grammar and dictionary he began to write when, as a young man, he first heard of the idea of a universal language. He also wrote a paper, never published, "On the Art of Opening all Locks," and then made a plan to defeat his own method. During all of his travels he never missed an opportunity to measure the pulse and breathing rate of any animals he happened to encounter, and prepared in skeleton form a "Table of Constants of the Class Mammalia."

Babbage made one excursion into the field of apologetics with an incomplete work entitled *The Ninth Bridgewater Treatise, A Fragment*, published in 1837. The regular Bridgewater series had been supported by a bequest which called for the preparation of eight treatises which would give evidence in favor of natural religion. Babbage decided to add a ninth, at his own expense, on the same general subject, but with particular arguments against the prejudice, which he felt was implied in the first volume of the series, that the pursuits of science, and of mathematics in particular, are unfavorable to religion.

He used his experiences with his calculating engine to bolster his arguments on the nature of miracles and in favor of design. As B. V. Bowden says, "he thought of God as a Programmer." He repeatedly alludes to the possibility of defining a series by such a complicated rule that the first hundred million terms might proceed according to an obvious scheme, and the next number violate it, while the rest of the sequence continued according to the first plan. He described the programming of a calculator for generating such a series. In this argument he felt he had shown a possible origin of miracles in a world otherwise controlled under God by orderly natural law.

In his autobiography Babbage jokingly traces his ancestry to the prehistoric flint workers because of his "inveterate habit of contriving tools." He reports that as a child he had a great desire to inquire into the causes of all events, and that his invariable question on receiving any new toy was "Mamma, what is inside of it?" If the answer did not satisfy him, the toy was broken open. He remembers as a small boy being fascinated by an exhibition of clockwork automata, especially one of a small figure of a silver lady dancing. He ran across the silver lady many years later, and acquired her for his drawing room, where she was dressed in elaborate robes and displayed on a pedestal in a glass case. She held a place of honor next to the portion of his Difference Engine which he also had on exhibit at home. He would set either or both of them into operation for the entertainment of his guests: the lady to dance, and the Engine to print a small table, and noted ruefully that on one occasion his English friends were gathered about the silver lady while an American and a Hollander studied the Difference Engine. Babbage recounts a conversation he once had with the Countess of Wilton and the Duke of Wellington, who had called at his home to see the Difference Engine. The Countess asked what he considered was his greatest difficulty in designing the machine. He replied that his greatest difficulty was not that of "contriving mechanism to execute each individual movement . . . but it really arose from the almost innumerable *combinations* amongst all these contrivances," and compared his problems to those of a general commanding a vast army in battle. He was pleased to have Wellington confirm his analysis.

VII. MACHINERY

JUST AS the mathematical machine-designing team of today soon becomes involved in a welter of problems about the properties of vacuum tubes and electronic circuits, so Babbage became deeply involved in the problems of the machine shop and the drafting room. During the course of the work many ingenious mechanical devices were perfected and even some of those that were rejected for use on the calculator were not entirely wasted, but were introduced with success into other machinery as, for example, into a spinning factory at Manchester. To create the great variety of new and complex forms with the required precision for the Difference Engine, a number of new tools to use with a lathe were invented. To test the "steadiness and truth" of the tool-holders used in making some key gun-metal plates of the Difference Engine, Babbage reports that he "had some dozen of the plates turned with a diamond point," and he was delighted to observe the resulting grating spectra or "Frauenhofer images," as he called them. With his own sketches and with drawings prepared by a full-time draftsman, Babbage placed the construction of the machine in the hands of the engineer Joseph Clement. Clement was one of the great machine-tool builders of the century, who earlier had been a draftsman for Henry Maudslay, the introducer of the slide rest and the screw cutting lathe. Babbage tells of an order Clement once received from America to construct a large screw in "the best possible manner." This he proceeded to do, according to his standards, with a precision, and consequently a bill, far greater than his customer expected. The customer was required to pay some hundreds of pounds, although he had anticipated a bill of twenty pounds at most! The mainstay of Clement's custom shop was the first large planing machine, although from the sums expended by Babbage it appears that the Difference Engine was one of the largest single jobs in Clement's shop, somewhere between one fifth and one third of its whole effort. In Babbage's own writings it tends to appear as though Clement were in fact a full-time employee of Babbage, but this seems to be inaccurate. Babbage broke with Clement in 1833 and seems never to have carried any further projects beyond the stage of drawings and experimental parts.

Among the workmen in Clement's shop was one J. Whitworth, who became Sir Joseph Whitworth, Bart., leader in the machine-tool industry in the nineteenth century. It was Whitworth who first brought about the standardization of screw threads, and the Whitworth thread remained the British standard until 1948. He insisted upon the use of gauge blocks, recognizing end measurement as better than measurement between scratch lines. Even in the 1830's he could work to standards of a micro-inch. He is frequently credited with the familiar machinist's scheme of preparing plane standard surfaces three at a time by hand scraping, but this ascription seems to be doubtful. Whitworth's independent career began when he left Clement, probably because of the curtailment of the Babbage contract, and set up his own shop at Manchester. His was probably the first shop to build machine tools mainly for sale to other tool manufacturers.

Babbage wrote a paper "On the Principles of Tools for Turning and Planing Metals" for a three-volume reference work on the lathe, published in 1846 by Holtzapffel & Co. The publisher acknowledges that "The cultivation of Mechanics by Gentlemen . . . has given rise to many ideas and suggestions on their part, which have led to valuable practical improvements," and offers instruction to amateurs in "Turning or Mechanical Manipulation generally," either at Holtzapffel's shop or at the gentlemen's private residences. The parallel is complete: like today's mathematical-machine builder, today's scientific hobbyist is apt to use vacuum tubes; he is more likely to build amplifiers than do ornamental turning on a lathe. The drawings which Babbage had for his machines covered over 400 square feet of surface. They were described by experts at that time as perhaps the best specimens of mechanical drawings ever executed, done with extraordinary ability and precision. In the course of preparing them, Babbage invented a scheme of mechanical notation to make clear in a drawing the action of all the moving parts of a piece of machinery. Since Babbage's machinery was particularly complex to describe in motion, he was extremely proud of his notation. He prepared and had printed a short paper describing his principles of mechanical notation, which he gave away in considerable numbers during the Exhibition of 1851, requesting readers to send him any criticisms or suggestions. This paper is reprinted on page 357 of this volume.

Babbage's most successful book, and in fact the only work of any consequence which he ever *completed*, was the *Economy of Manufactures and Machinery*, published in 1832. Only one brief excerpt from this work is reproduced in the present volume (page 315). Although originally intended as a series of lectures at Cambridge, Babbage published the work in book form, with a condensed version prepared as a prefix to the appropriate volume of the *Encyclopedia Metropolitana*. It ran through several editions, was reprinted in the United States, and was translated into German, French, Italian, and Spanish, in spite of the trouble Babbage reports having with booksellers because of his chapter analyzing the book trade. As a result of supervising the construction of his own Engine, he became interested in the general problems of manufacturing and visited factories in England and on the Continent. He learned from a workman how to punch a hole in a sheet of glass without breaking it, and found a demonstration of this skill a useful method of winning the confidence of the various craftsmen with whom he spoke. (See page 129 for this interesting method.) The book includes a detailed description and classification of the tools and machinery used in various manufacturing operations which he observed, together with a discussion of the "economical principles of manufacturing." In the mood of an operational research man of today, Babbage takes to pieces the manufacture of pins—the operations involved, the kinds of skill required, the expense of each process, and the direction for improvements in the then current practices. He makes a number of suggestions about methods for analyzing factories and processes and finding the proper size and location of factories, and stresses the need for studying the work of contemporary inventors in other countries. He points out that the division of labor, so important for manufacturing, can be applied also to mental operations, and cites as an example the work of G. F. Prony, director of the École des Ponts et Chaussées, who successfully organized three groups of workers—skilled, semi-skilled, and unskilled—to prepare a great set of mathematical tables. Prony began work in 1784 under the same impetus which led to the establishment of the metric system in revolutionary France. He undertook to construct elaborate trigonometric tables based on the division of the quadrant into a hundred parts. A necessary auxiliary work was an unprecedented table of logarithms. This tabulated the logarithms of the natural numbers up to 200,000, carried out to fourteen decimal places. Prony realized that life was too short for such an effort (one sixth of that work had cost Briggs six or eight years). The story goes that, happening to read the new book of Adam Smith on the division of labor, he proceeded to organize the computations on this basis. His most skilled handful included mathematicians of the stature of Legendre. Their task was, of course, no mere computation but the choice of the best analytical expressions for numerical evaluation. Their formulae were transmitted to a group of about eight well-trained computers who put them into the appropriate numerical form. The computers of unskilled kind varied in number from 60 to 80. Their task was nothing more than addition and subtraction, according to the rules that were specified. It seems that nine tenths of them literally knew no more than addition and subtraction, and these turned out to be the best computers. Two teams worked independently and in duplicate and finished in about two years. The final "Tables du Cadastre" were never published, but remained in two copies, each of seventeen manuscript folio volumes. These were frequently consulted as checks by other computers, including Babbage himself who visited the Observatory in Paris on this errand.

Also included in the *Economy of Manufactures* is a panegyric for the "Science of Calculation . . . which must ultimately govern the whole of the application of Science to the Arts of Life." Babbage reports as one of the best compliments he ever received on the book a remark by an English workman he met, who said "that book made me think." One profoundly practical result of his operational research method was the introduction of the penny post in England; Sir Rowland Hill was encouraged to do this by Babbage's analysis of postal operations, which showed that the cost of handling the mail in the post office was greater than the cost of transportation. This pioneer work, *Economy of Manufactures*, is good reading even today.

VIII. OTHER INTERESTS

Babbage made a number of suggestions for practical inventions of various kinds. Much interested in railroads, he attended the opening of the Manchester and Liverpool Railway and made several suggestions for ways of preventing accidents, including a method for separating a derailed engine from a train. In 1838 he was consulted by Isambard Brunel and the directors of the Great Western Railroad and spent five months doing experiments, which consisted largely of tracing on paper the curves of motion made by the special car in which he worked. On the basis of these experiments, he recommended use of a broad gauge and proposed an automatic speed-recording device for every engine. He suggested a numerical system of occulting lighthouses, and sent a description of his scheme to the authorities of twelve maritime countries. The United States Congress appropriated $5,000 to try his scheme experimentally, and the results of these experiments were published in 1861 in an extremely favorable report recommending adoption by the U.S. Lighthouse Board. An experience in a diving bell in 1818 led Babbage to consider the question of submarine navigation, and he prepared drawings and a description of an open submarine vessel with air for four persons for two days. Such a vessel, he thought, could be screw-propelled, and might enter a harbor and destroy even iron ships! He also suggested the use of a rocket apparatus to boost projectiles and the use of mirrors for indirect fire for artillery. Once at an opera, much bored by the performance, Babbage had the notion of using colored lights in the theater. He did some experiments, using cells formed by pieces of parallel glass filled with solutions of various colored salts, and even devised a rainbow dance to demonstrate this new technique.

Babbage did some physics in Cambridge, and published a paper with Herschel in 1825 on magnetization arising during rotation, based on experiments of Arago. Babbage was also much interested in geology and astronomy. After the eclipse of 1851 he suggested the germ of the idea of the coronagraph for seeing the sun's prominences without an eclipse, but he had not at all analyzed the problems of scattered light. It seemed possible to him that one could get a record of the succession of hot and cold years in the past by examining and comparing tree rings in ancient forests (see page 367); this method was rediscovered early in this century and used to great advantage in southwestern United States. He wandered once again into the field of archaeology in his last scientific paper, entitled "On Remains of Human Art, mixed with the Bones of Extinct Races of Animals," published in 1859. Babbage once proposed to write a novel in order to help finance the completion of his Analytical Engine. He planned to devote a year to preparing a three-volume novel with illustrations, which was to earn 5,000 pounds. He was discouraged from pursuing this project by a poet friend wise in the pitfalls of literary fortune.

Unlike Darwin, who wrote his autobiography for his own children, with no thought of publication, Babbage says that he wrote his *Passages from the Life of a Philosopher* to "render . . . less unpalatable" the history of his calculating machines by an account of his own "experience amongst various classes of society." He was over seventy when he prepared this collection of anecdotes and ideas, and more obsessed than ever with his beloved engines. The book's characteristic combination of peevishness and humor is apparent as early as the title page. Babbage was a bitter man, and his autobiography is as much a record of his disappointments as of his achievements. The largest part of the book is, of course, devoted to his engines, with an account of their theory and principles of construction, and the sad tale of their neglect by the British Government. In 1832, and again in 1834, he ran unsuccessfully for Parliament on a Liberal (Whig) platform, and he includes in his autobiography parts of an amusing electioneering play used in connection with his campaign. In the play, entitled *Politics and Poetry* or *The Decline of Science*, Babbage is characterized as Turnstile, "a fellow of some spirit; and devilish proud," and again as "a sort of a philosopher—that wants to be a man of the world." In a chapter entitled "Street Nuisances," Babbage describes his one-man battle against street musicians, which brought him as much fame, in London at least, as all his scientific accomplishments combined. Babbage maintained that his ideas vanished when the organ-grinder began to play, and calculated that such interruptions destroyed one fourth of his working power. He waged a vigorous campaign of letters to newspapers and to members of Parliament, and personally hauled many individual offenders before a magistrate. One of the latter once asked Babbage whether a man's brain would be injured by listening to a hand organ, and Babbage replied "certainly not, for the obvious reason that no man having a brain ever listened to street musicians." That this particular battle of Babbage's was not taken seriously is made clear by his obituary notice in the sober London *Times* in 1871, which remarks somewhat cruelly in the first paragraph that Babbage lived to be almost 80 "in spite of organ-grinding persecutions."

IX. DEFENSE OF SCIENCE

EVEN BEFORE he had a personal grievance against the British Government for its failure to support his own machine, Babbage had sharply criticized the Government for its neglect of science and scientists. Never a man to avoid a fight for what he considered a good cause, Babbage had for years led an assault on the decline of science in England. He published two stinging tracts, *Reflections on the Decline of Science in England, and on some of its Causes* (1830), and *The Exposition of 1851; or Views of the Industry, the Science and the Government of England* (1851). Bitter because few Englishmen pursued science for its own sake, he attacked the neglect of science in the educational system and urged Government subsidies for scientists. He felt that scientists should hold many Government posts and that pure science should be encouraged. "It is of the very nature of knowledge that the recondite and apparently useless acquisition of today becomes part of the popular food of a succeeding generation," he wrote. Chief target of his diatribes on the neglect of science in England was the Royal Society, to which he had been elected while still at Cambridge. He submitted a plan for sweeping reforms to the Society, which rejected it without discussion. His plan included such items as requirements for publication of scientific articles as a test for membership, instituting democratic election procedures, and free discussion of policies at meetings. Infuriated by the Society's refusal to consider his plan, he continued to condemn what he termed the intrigues of the Society, pronounced its secretaries third-rate, and its president elected on the

basis of rank rather than scientific interests. Babbage would perhaps be disappointed to find that within the last decade the BAAS which he helped to found was headed, nominally at least, by the Duke of Edinburgh! Babbage described the Council of the Royal Society as "a collection of men who elect each other to office and then dine together at the expense of the society to praise each other over wine and to give each other medals." Although some of Babbage's accusations against the Royal Society and the Government for their neglect of science were exaggerated, his position was fundamentally sound, and he found a good deal of support. Babbage has been aptly characterized as "a scientific gadfly" who "successfully needled his contemporaries into general agreement."

Babbage blamed the Royal Society for conditions at the Royal Observatory at Greenwich; on one occasion he had been refused a copy of some of the Greenwich observations, and later located five tons of the Greenwich tables in a shop which had bought them by the pound for making pasteboard. Babbage remarked that the Astronomer Royal was certainly the man best fitted to decide what should be done with his own publications, but did not think it possible to invent a more extravagant way of compensating a public servant than to establish an observatory and computing center for the production and printing of astronomical tables simply as a source of wastepaper! He had no great love for the then Astronomer Royal, Sir George Airy, in any case, for that official had recommended no further Government support for the Difference Engine, and had refused to consider the possibility of mechanizing his own computations.

X. CONCLUSION

BABBAGE ONCE said that he would gladly give up the remainder of his life if he could be allowed to live three days five hundred years hence and be provided with a scientific guide to explain the discoveries made since his death. He judged that the progress to be recorded would be immense, since science tends to go on with constantly increasing rapidity, and Babbage always took a confident view about human progress. The wide range of his practical and scientific interests and his clear commitment to the notion that careful analysis, mathematical procedures, and statistical calculations could be reliable guides in almost all facets of practical and productive life give him still a wonderful modernity.

More than one spiritual contemporary of Babbage is flying today from site to site on the missions of the Atomic Energy Commission and the Rand Corporation. His whole story bears witness to the strong interaction between purely scientific innovation, on the one hand, and the social fabric of current technology, public understanding, and support on the other. His great engines never cranked out answers, for ingenuity can transcend but it cannot ignore its context. Yet Charles Babbage's monument is not the dusty controversy of the books, nor priority in a mushrooming branch of science, nor the few wheels in the museum. His monument, not wholly beautiful, but very grand, is the kind of coupled research and development that is epitomized today, as it was foreshadowed in his time, by the big digital computers.

September, 1959
Ithaca, New York

PHILIP AND EMILY MORRISON

HISTORY OF PUNCH CARDS

"... the Analytical Engine *weaves Algebraical patterns*, just as the Jacquard-loom weaves flowers and leaves ..."

ADA AUGUSTA, COUNTESS OF LOVELACE

THE USE of punched holes in paper cards for the digital storage of information can be traced step by step back to the early eighteenth century.

That history does *not* begin with writing; it is directly related rather to the weaving of elaborate figured silks. For the essence of the problem is the ability for easy storage of large amounts of information to be read, not visually, but mechanically. Writing and other graphic arts are intended essentially for visual examination. Even in these days it is plain that use of merely optical coupling is more complex than direct mechanical means for conveying information to machines.

The weaving of ornamentally figured silk textiles was well developed in China as early as 1000 B.C. The product of this art, though probably not the looms which made it possible, is known to have appeared in the West by late Roman times. A complex figure on the cloth implies that in the weaving process a specified set of the longitudinal threads (the warp) was lifted to allow the passage of the transverse weft thread to form each single line of the final pattern. The strong, fine, lustrous silk fiber has been the principal medium which made the elaborate labor of complex ornamental weaving worthwhile. Such weaving was always at least a two-man job. It employed a special loom, called the drawloom, which was certainly used in the Italian silk centers in the Middle Ages, but which represents a tradition going back, at least by analogy, to the earliest Chinese devices. In the drawloom a cord is attached to each warp thread. These cords are united in groups appropriate to the pattern to be woven. When these cords are pulled in the correct sequence, the weaver is able to throw the shuttle, with its weft thread attached, through the opening made by the lifted warp threads. An unskilled assistant to the weaver pulls the cords as indicated by a painted chart usually made on squared paper, one square to each thread, both warp and weft. Squared paper was used even before the invention of printing.

The preparation of this squared paper for the drawboy might be aided by the use of a simple stencil, in which holes are pricked to allow the quick copying of the coordinate mesh. It must be remembered that information is needed in large amounts for the weaving of a complex ornamental pattern. Even the most ancient Chinese examples required that about 1,500 different warp threads be lifted in various combinations as the weaving proceeded. The design repeats after a number of weft threads, but the drawboy had to pull 40 or 50 distinct bundles made of these 1,500 lifting cords in the correct sequence for each transverse weft. In the seventeenth century it took a skilled weaver two or three weeks to set up a drawloom for a particular pattern. In 1725 Basile Bouchon, in the silk center of Lyons, designed a mechanism for automatically selecting the cords to be raised. The cords were passed through eyes in a row of horizontal needles arranged to slide in a box. The selection of the cord was made by pressing against these needles a roll of perforated paper. On this roll a set of punched holes, spaced to fit the needles, was perforated line after line, as in a player piano roll or a monotype type-casting machine, both of the later nineteenth century. It may be that M. Bouchon got his idea from the squared-paper stencils on which the patterns were pricked. Those needles which entered the punched holes passed through freely and did not raise their connected warp threads, while the others were active. Thus the pattern could be picked out, weft thread by weft thread, one to each line of holes. Only three years later another Lyons inventor, one M. Falcon, extended the scheme to allow the use of several long rows of needles, one row above the other. Obviously this could be done more neatly by using a rectangular card instead of a paper roll. Using a perforated platen held in the assistant's hand, a card was pressed against the needles. This is certainly the full punched-card principle; the obvious extension to a long series of cards, all strung together, was already Falcon's.

It was not until 1801 that J. M. Jacquard of Lyons made a fully successful automatic drawloom. He took over the cards from Falcon, but very much elaborated the mechanics of the apparatus, so that the loom became a one-man operation. Jacquard looms were made by the tens of thousands in the early decades of the nineteenth century; indeed, they are even more common today. We know directly from Babbage that it was the Jacquard string of punched cards actuating the lifting cords of the silk loom which inspired his use of the same principle for the Analytical Engine. He was very proud of a remarkable woven silk portrait which he owned, showing the inventor Jacquard surrounded by the machines of his trade. This work was woven with about 1,000 threads to the inch and resembled a line engraving in fineness of detail. A total of 24,000 cards, each one capable of receiving 1,050 punch-holes, was used to weave its five square feet. This truly extraordinary display fascinated Babbage and surely did much to convince him of the practicality of complex information storage through the mechanical perusal of punched cards.

Babbage never built a punched-card machine, but the inventor, patentee, and co-founder of the earliest practical punched-card tabulating machine may have been influenced by Babbage's work, perhaps through the summary report of the Committee of the British Association, published in 1878; more probably he took his ideas directly from the Jacquard loom. Herman Hollerith went to the U. S. Patent Office to begin serious work on punch-card tabulation in the early 1880's. By 1890 crude Hollerith machines (looking not unlike the Falcon drawloom mechanism) were in practical use at the Census Bureau, and Hollerith and other punch-card machines were extensively employed thereafter both in the United States and abroad. Contemporary punch-card machines of all manufacturers stem from one or another of these early devices.

P.M.
E.M.