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BABBAGE AS A COMPUTER PIONEER

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Summary

This paper is primarily concerned with Babbage's plans for the Analytical Engine. It is based on an examination of Babbage's surviving notebooks and drawings and includes much unpublished material on the "directive part" of the engine--what would now be called the control. The paper ends with an evaluation of Babbage's work in the light of modern developments.

In writing of Babbage as a computer pioneer one must at once admit that his work, however brilliant and original, was without influence on the modern development of computers. The principles that Babbage elucidated, but regrettably failed to communicate, had to be rediscovered by the men who, 100 years later, built the first automatic computers. The ultimate loss was not perhaps in itself a great one, since, as soon as progress of a practical sort was achieved, the subject quickly developed far beyond the point to which Babbage had taken it. More important was the fact that Babbage's projected image became one of failure, with the result that others were discouraged from thinking along similar lines and the eventual development of automatic computers was delayed.

I shall be concerned with Babbage's personal achievements as a computer man, but it is important to remember that he was much else besides. His interests extended to railways, insurance, economics, optics, and many other subjects. Irascible and self-important he could certainly be, but there was another side to his character. Professor Owen [1894 vol. 1, 291] is quoted as referring to him as 'looking beaming throughout' at a childrens' party, and his humanity comes out clearly enough in his autobiography.

Around 1834, when he was 42 years old, Babbage's thinking on calculating machines underwent a profound development. Up to that time he had been working on the Difference Engine, which was essentially a special purpose device intended for the tabulation of mathematical functions. Thereafter he began to work on the Analytical Engine which was to be a truly general-purpose digital computer. The Analytical Engine came to dominate his thoughts more and more as he appreciated the possibilities that were opening up. In May 1835, M. Quetelet read to the Académie Royale des Sciences in Brussels a letter from Babbage that he had just received; in this letter Babbage said: " ... I have given up all other subjects of inquiry ... I am myself astonished at the power that I have been able to give to the machine ... I would not have believed this possible a year ago ... The greatest difficulties of the invention are already overcome, but I shall need several more months to complete all the details and make the drawings" [Quetelet 1835]. Babbage did not realize then that he would be working on drawings for the Analytical Engine until the end of his life.

THE DIFFERENCE ENGINE

In the preparation of mathematical tables, it is usually unnecessary to compute from the fundamental mathematical formulae all the tabular entries that will be finally required. Instead, only every tenth value (say) is computed in this way. These are known as *pivotal values* and the intervening values are supplied by interpolation. Babbage's Difference Engine was designed to perform this last task; it would be supplied with the pivotal values, or rather with differences calculated from them, and would automatically produce stereo moulds from which plates for printing the table could be made. The partial mechanization of the printing process and the avoidance thereby of typesetting errors was an essential part of the proposal.

Babbage conceived the idea for a difference engine during his student days in Cambridge. After going down, he made a small model to demonstrate the principle. In 1823 when he was 31 years old, he succeeded in obtaining financial support from the British Government for the construction of a full-scale machine. At first, construction proceeded smoothly in the workshop of J. Clement, whom Babbage employed for the purpose. It was not very clear what the extent of the Government's original commitment actually was, and Babbage had continually to negotiate for more money. A good many years went by and the machine was still not completed, although successive governments had spent some £17,000 on it. Eventually the government of the day decided to abandon the project. The decision came as a great blow to Babbage and he did not take it well. He continued to protest in various writings for the rest of his life. One sympathizes with him, but one sees also the point of view of those who had to take the decision. Babbage strongly suspected that G. B. Airy, the Astronomer Royal, had something to do with it, and he was right. The following passage appears in Airy's autobiography published in 1896: "On September 15th [1842] Mr. Goulburn, Chancellor of the Exchequer, asked my opinion on the utility of Babbage's calculating machine and the propriety of expending further sums of money on it. I replied entering fully into the matter and giving my opinion that it was worthless" [Airy 1896, 152].

THE ANALYTICAL ENGINE

Work on the Difference Engine had actually ceased some nine years earlier on account of difficulties that had arisen between Babbage and his engineer over a move to a new building and Babbage's reluctance to advance further money. When the work stopped, Babbage found himself at a loose end and his active mind began to work along a new line. He had, for some time, been intrigued by the idea of a difference engine 'eating its own tail'. This would be achieved by establishing a connection between the register in which the result was accumulated and the register holding the highest order difference. This difference would no longer be constant and the engine would therefore be capable of generating functions of a wider class. It would, in fact, be a form of digital differential analyser. It is to Babbage's credit that he did not elaborate this idea, but, taking it as a starting point, moved rapidly to the concept of a general-purpose automatic calculating machine, namely the Analytical Engine. He found himself in a new world as endless possibilities began to reveal themselves. In a sense, these new thoughts put the final seal on the fate of the Difference Engine, already in deep enough trouble. Babbage saw clearly that the new principles that he was developing would enable a much simpler difference engine to be constructed and he felt that the government should be informed of this fact. Without doubt, this additional complication contributed to the decision that has just been referred to. Babbage continued to see the need for a special-purpose device for aiding in the preparation of mathematical tables, and gave serious thought over the years to the design of what he referred to as 'Difference Engine number 2'. It is, however, the Analytical Engine that claims our interest now.

Babbage was a prolific writer and expressed himself in print on many subjects. The treatment in his published work of the Analytical Engine was, however, on a very general level, and nowhere did he go into detail about the means by which his objectives were to be realized [1]. I do not think that this was because of secretiveness on Babbage's part, since he appears to have been very willing to explain his ideas to those who were prepared to listen. In 1840, he was invited to visit Turin on the occasion of a meeting of Italian scientists and engineers. He took with him some of his drawings for the Analytical Engine and held a series of 'seminars' in his lodgings at which he explained the way the machine would be used to solve problems. L. F. Menabrea, then a young military engineer, took details of these presentations and, with Babbage's approval, published an account in 1842 in the *Bibliothèque Univérselle de Genève*. This article was ably translated by Lady Lovelace, who had studied mathematics under the guidance of Mary Somerville [1873, 154]. Lady Lovelace was some 23 years younger than Babbage and evidently knew him well. She further elucidated Menabrea's explanations with some extensive notes of her own, and published the translation and notes in Taylor's *Scientific Memoirs* in 1843.

It is through the publication just mentioned that we derive our main knowledge of the type of problem that Babbage had in mind might be solved on the Analytical Engine, and of the way in which problems would be prepared for the machine. Indeed, Babbage regarded it as saying all that need be said on the subject. However, the examples given are outlines of what we would now call programs, rather than actual programs, and the way in which the various sections would be articulated to form loops is far from clear [2]. In fact, in his published writings, Babbage gives very little idea of how the flow of calculation would be controlled. He is content to state that he would adopt the Jacquard mechanism that had recently come into use for controlling automatic looms. As D. R. Hartree once pointed out, although Babbage gives names to other parts of the engine, he does not, in his published work, have a specific name for what we would now refer to as the control. From Babbage's publications, one would get the impression that he took the control for granted and had not thought out its details.

A very different impression is created if one turns to Babbage's unpublished notebooks and drawings, now in the Science Museum Library [3]. It at once becomes clear that Babbage was moving in a world of logical design and system architecture, and was familiar with and had solutions for problems that were not to be discussed in the literature for another 100 years. It is only by studying these notebooks that any idea can be formed of Babbage's stature as a computer pioneer. The notebooks are described either as scribbling books or as sketchbooks and in them Babbage worked out his ideas. Many of the pages are covered with rough sketches and jottings, and are not very informative; from time to time, however, Babbage becomes more coherent and in concise notes summarizes his ideas on some particular point.

Babbage had a pretty good general idea of the design of the Analytical Engine by the latter part of 1835. The true depth of the problems on which he had to work then began to reveal itself. Babbage never stopped grappling with these problems, but the next nine years are of particular interest and are well covered in the notebooks. It is with this period that I am primarily concerned in this paper. In studying the notebooks one is not studying a complete design for the Analytical Engine but rather the workings of Babbage's mind as he progressed towards such a design. The notes were, of course, written by Babbage solely for his own use. Reading them one can often get a vivid understanding of the detailed point that Babbage was thinking about at the time, but the overall plan remains shadowy. This is no doubt because Babbage had no need to write down what was perfectly clear and familiar to himself. Since the problems that he wrote about are those that we still have today, one has to be continually on one's guard against jumping to conclusions and assuming, in the light of modern knowledge, that he meant something that he did not in fact mean. Partly to avoid this danger and partly to give something of the flavour of Babbage's notebooks, I have in the descriptions that follow retained some of Babbage's own terminology.

In addition to the notebooks, there are a large number of drawings of the Analytical Engine. Most of them, however, refer to details, and they are not as illuninating as one would wish about the general arrangement of the engine. However, in addition to the drawings, there are a number of parcels of 'notations'. These are written in a system of mechanical notation that Babbage invented and was very proud of. He considered it as one of his principal contributions to science, and published an account of it in the *Philosophical Transactions* in 1826. His son, Major-General Henry P. Babbage, claimed in 1888 that anyone who mastered this notation would find in the drawings and the notations a complete description of the Analytical Engine as it was finally conceived. This was no doubt the case while either Babbage or his son were still around to clear up any difficulties. Whether at this distance of time it would still be true I do not know. The task of studying the notations and drawings in detail would be a heavy one and, not having attempted it, I am conscious of the fact that I may be failing to do Babbage justice. I would certainly have incurred his displeasure.

THE STORE AND THE MILL

The Difference Engine consisted of a number of registers each with its own adding mechanism connected so as to operate on a fixed program. In considering the more general device, Babbage early realized that economy would be served by separating the functions of storage and arithmetic calculation. He therefore proposed that the Analytical Engine should contain a *store* and a separate arithmetic unit or *mill*. Each register in the store would consist of a set of wheels mounted on a vertical shaft, there being one wheel for each decimal digit. Each wheel would have ten distinguishable positions, corresponding to the digits 0 to 9. Babbage referred to the registers as axes.

In order to transfer a number from an axis in the store to another axis in the mill, or elsewhere, it was first necessary to bring the wheels of the second axis to their zero position. The wheels of the store axis would then be raised so that teeth cut into them would engage with teeth in a set of racks capable of moving horizontally. The wheels intended to receive a number would also be raised to engage either the racks just referred to or another set of racks or wheels connected to them. The wheels of the store would then be turned to zero, the result being to turn by an equal amount the wheels in the receiving axis. This axis would then be lowered and thereby disconnected from the racks. If it were desired to leave zero in the store, the wheels in the store axis would also be lowered and the racks then returned to their original position. If, however, a copy of the number were to be retained in the store, the lowering of the store wheels would be delayed until the racks had returned. This we recognize as an example of a store with destructive reading and re-writing.

The design of the mill afforded Babbage many problems on which to exercise his wits. He was particularly proud of his discovery of a principle whereby the complete operation of carry-over during the process of addition might be effected in one turn of the shaft instead of taking one turn for each decimal place to be covered. This was especially important to him as a time saver since he was contemplating having 50 decimal places in his numbers. He called it *anticipating carriage*. In 'Passages from the life of a philosopher', he describes the intense mental activity that led to this breakthrough, not omitting to record that his assistant, to whom he confided his hopes of a successful outcome, formed the opinion that he was taking leave of his senses [Babbage, C 1864, 114-115; Morrison & Morrison 1961, 53-54].

Babbage discovered the principle of anticipating carriage as early as October 1834, and over the years worked out a number of ways in which it could be implemented. Part of one of his drawings illustrating such an implementation is reproduced in Plate I, and Babbage's own explanation of its working is given at the end of the paper [4]. Nowhere else does Babbage give such a careful explanation of one of the drawings.

Consideration of the best way to perform multiplication and division occupied a good deal of Babbage's time. He considered that multiplication by successive addition would be too slow, except perhaps in a very unambitious engine, and proposed that the nine simple multiples of the multiplicand should be first generated and stored on axes. As each digit of the multiplier was taken into consideration, a selecting mechanism would select the correct multiple to be added to the partial product. Babbage referred to this as multiplication by table.

The logical problems of doing arithmetic in the scale of 10 using elements with 10 states were studied in the 1940's by the designers of the Automatic Sequence Controlled Calculator and of the ENIAC, and their solutions will be found in the literature. It is interesting to note that a method of multiplication by table was used in the former machine [Manual 1946, 22]. The introduction of binary coded decimal and pure binary representation rendered this and other techniques obsolete for large-scale computers. Babbage did not move in such a direction, although he was not entirely satisfied with the scale of 10 as an internal representation. Under the date 15 March 1838 he has the following note: "To be examined whether, an arithmetic whose basis were 12, 16 or any other number being adopted, the operations might not be performed in shorter time notwithstanding the time consumed in converting the numbers out of the decimal scale and in re-converting the results into that scale. The question of a scale whose basis is 100 has already been considered" [Babbage Sketchbook II, p. 19 from back; also Minutes]. Twenty years later on 1 January 1858 he sums the matter up as follows: "Early in the original enquiry I had examined the relative value of various bases of notation in arithmetic, 10, 12, 16, 20, etc., and had contrived a carriage for an engine with base 100 so that each figure wheel would have contained two places of figures. These were given up for reasons then stated in other papers. I had also tried bases less than 10 as 5, 4, 3, 2, but these were rejected on account of the great multitudes of wheels required" [Babbage Cambridge Notebook, 452]. Babbage did not view the scale of two as having any special significance, but simply considered it along with other scales.

THE DIRECTIVE PART

For the control of the engine, Babbage's first idea was to use a large drum with adjustable stops, somewhat on the principle of the barrel organ [5]. The drum would be moved round one step at a time. At each step, the adjustable stops would indicate what variables in the store were concerned, and subsidiary drums (also with adjustable stops), one for each variable, would indicate the exact nature of the operation to be performed. It was only a few months, however, before Babbage took the momentous step of deciding to use the punched card mechanisms from the Jacquard loom instead of drums. He dates his decision to 30 June/1 July 1836. He lists the advantages of using Jacquard cards as follows: "It is easier to punch pasteboard than to screw on a multitude of studs. When once the formula has been made and verified, it need never be made again until worn out. The change from one formula to another, when both have been previously made, is done in a very short time. There will be no backing [that is, reversing] of the drums, and the Jacquard pasteboards will circulate. Every formula ever put into the engine will be preserved. The extent of the formulae is almost unbounded" [Babbage Sketchbooks XIII]. Perhaps it was because the idea of using Jacquard cards came so early in Babbage's thinking about the Analytical Engine that he did not make more of it as a breakthrough. In his published works there is no indication that he had ever considered the idea of using drums.

In a Jacquard mechanism the punched cards are strung together to make a chain, suspended over a polygonal roller or *prism*. The prism is capable of swinging backwards and forwards in a direction perpendicular to its axis. When it moves forward it pushes the current card against a matrix of rods or *needles*; the needles that are not opposite holes in the card are pushed forward while those that are opposite holes remain at rest. In one important respect Babbage generalized the concept of the Jacquard mechanism by arranging that the cards could be stepped backwards as well as forwards so that repetitions and loops could be established. Babbage never uses the metaphor of reading applied to a card, but always speaks of the card *advancing*. This refers to the forward motion just described. Since in this instance the modern term is convenient and unlikely to be misleading I shall sometimes use it. Similarly, I shall speak of the card mechanism being stepped on or stepped back, whereas Babbage would refer to the prism being turned or backed.

The resemblances between the Analytical Engine and its sytem of programming and their modern counterparts must not blind us to the fact that there are also fundamental differences. Babbage never arrived at the idea so familiar to us today of an instruction consisting of an operation field and one or more address fields bound together as a unit. He had separate cards, and separate Jacquard mechanisms, for specifying operations and for specifying variables; the two mechanisms did not necessarily step together. Babbage did not have the formal concept of program in our sense, and did not, therefore, have any corresponding word. He thought in terms of setting up the engine to do a particular job such as evaluating on algebraic formula, and used such phrases as 'the operations required by the algebraic formula'. This, or perhaps the tabulation of a series of values, would be a typical task for the engine; it would be well within its power as limited by its operating speed, this being sufficiently indicated by saying that a multiplication would take about a minute [6]. Babbage did not and could not in any way foresee the long and elaborate programs that we know today.

The operation cards would control the action of the machine as a whole; they would, for example, cause the mill to multiply together two numbers that had already been transferred into it, or the printer to print a number. If the operation required one of the axes of the store to *give off*, that is to transmit a number to some other part of the engine, or to *receive* a number from another part, then the appropriate axis would be selected by a suitably punched variable card.

Since the two card mechanisms did not necessarily step on together, one could have loops of operations independently of loops of variables. For example, Babbage had an operation called *receive into store* that caused a sequence of number cards--placed on a third Jacquard mechanism reserved for the purpose--to be read and the numbers to be placed in the store. One operation card was used for this purpose and one variable card for each of the numbers to be read. The operation card would advance (that is, be read) repeatedly, while both number cards and variable cards would be stepped on after each number had been read. Similarly, it would be possible for the operation card mechanism to be stepped on and the variable card mechanism to be left where it was, so that the same variable would be used in two or more operations. The suggestion that operation and variables should be combined on the same card would probably have seemed to Babbage to cause an unnecessary restriction of flexibility.

The sequencing required to complete each operation was to be controlled by a *barrel*. This was a small drum with fixed stops and Babbage thought of it as being mounted with its axis vertical; each vertical row of stops corresponded to one of the individual sub-operations needed to complete the operation. Babbage refers to these rows of stops as *verticals*. As soon as an operation card has been read, a system of detents enabled the barrel to rotate so that the first vertical of the train of verticals corresponding to the operation called for was in position. The barrel then advanced, that is, moved bodily sideways on its axis, so that the stops pushed rods that would initiate the correct sequence of sub-operations. A vertical could *send to* another vertical, that is, cause the barrel to rotate so that the second vertical was ready to advance [7].

The card mechanisms would not work autonomously but would be placed under the control of the barrel. Not only would the cards advance 'by order of barrel' but the prisms would turn on or back when ordered to do so by the barrel.

It is tempting to use modern terminology and to regard the barrel as a control memory and the verticals as representing micro-instructions. Indeed, this is what they are. However, Babbage had no general concept of microprogramming any more than he had any general concept of ordinary programming. Nor did he intend to centralize the control of the engine using a single barrel. He would use barrels wherever they were convenient, and, in particular, there would be a barrel associated with the mill. The principal barrel would initiate cycles (controlled by cams) that might themselves involve the advancing of another barrel. Babbage speaks of a short cycle designed for add and carry, and of a long cycle sufficient to encompass operations needing more steps. The initial vertical of the principal barrel corresponding to each operation would determine what cycle was to ensue. Babbage describes a somewhat dubious mechanical means, depending on wheels with moveable teeth, whereby the correct cycle might be selected [Babbage Sketchbook V, 37, 27 July 1841].

One of the more illuminating of Babbage's drawings (no. 94) is reproduced in Figure 2, and described at the end of the paper. The drawing is dated August 1841 and it conveys very well the flavour of Babbage's mechanical thinking at the period.

CARD COUNTING APPARATUS

In order to control the repeated advancing (or reading) of the cards, counters are necessary. During the period that we are studying, Babbage's thoughts on this subject were in a state of active development. The following is an attempt to re-construct some of the main threads, although it is not always possible to be sure exactly how to interpret Babbage's notes.

Each card mechanism was to have associated with it a *card counting apparatus* abbreviated to CCAp. The CCAp would receive an integer known as an index. When a card advanced, unity would be subtracted from the index in the CCAp. Eventually the index would be reduced to zero, an event which Babbage referred to as the CCAp *running up*. The running up would cause a *conditional arm* to move and set an interposer so that on a subsequent advance of the barrel the prism of the card mechanism would be caused to rotate. The next card would then be in position ready to advance [8]. Thus, the index associated with a card, and placed in the CCAp, would determine the number of times that card was to be read.

At first Babbage intended that indices should be punched on to separate cards, but later he proposed that operation and variable cards should carry their own indices. This led to many fewer cards being required for a formula. When a card first advanced, the index punched on it would be communicated to the appropriate CCAp; the connection between the card mechanism and the CCAp would then be broken, and, on subsequent advances of the card, the number in the CCAp would be reduced by one. In many cases, of course, the index punched on a card would be unity [9].

Apparently one of the things that made Babbage decide that it was practicable to dispense with separate index cards was that he saw a way whereby room could be found for indices less than 1000 to be punched on the operation and variable cards themselves [10]. He proposed to use a scale based on the weights 1, 3, 9, with extra bits to indicate that the two former were to be reversed in sign. Thus five holes in the card, one for each weight and two for reversing the two smaller weights, would be required for each decimal digit to be punched. I cannot conceive what it was about this highly odd code that appealed to Babbage in the present context. Earlier he had mentioned the possibility of using a much simpler binary code with only four binary digits for each decimal digit, namely the code in which the binary digits have weights 1, 2, 3, 4 respectively [11]. I do not know whether the use of the 1, 3, 9 code as a passing idea, or a firm decision. The fact that he could consider such a code does, however, illustrate the sophistication of his thought.

Since numbers are necessarily punched on to cards in a binary code, a means for converting this code to the displacement code used on the racks and in the axes is necessary. Babbage uses *sectors*, which is his term for gear wheels with an incomplete circle of teeth. The four digit code mentioned in the last paragraph would need four sectors with 1, 2, 3, 4 teeth respective ly, and these would act on the rack sequentially. The 1, 3, 9 code would require three sectors, two of which would be capable of being reversed.

Babbage started by regarding CCAps as associated with particular card mechanisms; later he thought of them rather more as generally available devices, and proposed a means whereby an index punched on any card could be directed to any CCAp [12]. He also proposed to make it possible to add an index into a CCAp, or to add or subtract an index in one CCAp from the index in another. The CCAps were therefore no longer simple counters but had full adders associated with them.

Babbage does not, however, appear to have appreciated the power that would be obtained if numbers computed in the mill could be transferred *via* the store to any CCAp. He did, in fact, at one time propose a connection from the store to CCAps, but regarded it as unnecessary when he had decided to make it possible for the index punched on an operation card to be sent to any CCAp [13]. In a scheme that Babbage considered in November 1843, there would be blank variable cards and blank operation cards known as index cards; the latter would be blank in the sense that they would not specify any arithmetic operation, but would be used for manipulating indices held in the CCAp. Babbage says "The object is to make the CCAp always convey its orders *through* the operation cards" [10]. It is not very clear what he means, but presumably the blank operation card would interrogate a CCAp and act accordingly, for example either backing or advancing a prism. The proposal (if I have interpreted it correctly) seems to us to represent a step forward, but by July 1844, Babbage had swung away from it and come back to the idea that the running up of a CCAp should act directly on a barrel [14]. This was probably because of the extra time that would be consumed. We are so used now to the elegant and simple way in which the flow of control is managed in the stored program computer--by means of conditional instructions that are executed sequentially with arithmetic instruction--that we may forget that this is made possible by the high speed of electronic circuits. It is, in fact, an example of the sacrifice (or utilization) of speed to buy simplicity. If such a system were implemented for a computer running at the mechanical speeds that Babbage had in mind, the computer would appear to be unnecessarily slow in operation. Alternative schemes would be preferred in which the sequencing instructions could be given in parallel with arithmetic instructions and their execution overlapped. This, in effect, was what Babbage achieved with his system of punching indices on operation and variable cards.

Among the many things that are obscure about Babbage's intentions in relation to the flow of control is the way in which he intended to provide for conditional situations in which the action to be taken depends on the change of sign of a computed number. He gives prominence to this type of situation in his account of the Turin discussions [Babbage 1864, 131-135; Morrison and Morrison 1961, 64-68] but fails to mention it explicitly in the notebooks. This may be because he did not regard the implementation as presenting any difficulty, but it would be nice to know exactly what he proposed. In one passage he refers to an operation called *approximation* [9] in which the index is communicated *via* the sectors to the mill instead of to a CCAp. It is possible that this operation resembles a modern conditional jump and causes the operation cards to be advanced or backed according as the index is greater than or less than the result already standing in the mill. On the other hand, the passage in question could equally well refer to an operation for approximate multiplication or division intended to be used when less than the full accuracy of the mill were required; there are many references in the notebooks to approximation in this sense.

THE OVERALL DESIGN

Babbage succeeded in achieving a good deal of modularity in his designs. Writing in 1888, his son, H. P. Babbage, says "The machine consists of many parts. I have found it easier myself to regard these parts as so many separate machines, driven by the same motive power and starting and stopping each other in every possible combination, but otherwise acting independently, though with a settled harmony, towards a desired result" [Babbage, H. P. 1889, 333. Morrison and Morrison 1961, 336]. There was, in consequence, some latitude in the way the individual units might be disposed, and Babbage drew up a number of plans. These are, unfortunately, not very informative, since they are highly schematic; perhaps someone versed in the details of the Mechanical Notation might be able to derive sufficient information from them to get a clear idea of what the machine as a whole would have been like.

An extremely early plan dated 6 August 1840 (lithographed in Paris in 1840 and included in Babbage, H. P. 1889) shows the machine occupying an area of some 10 ft by 5 ft. In the centre of the machine are concentric toothed wheels 2 ft in diameter, with the various units grouped round them. These wheels provide communication for data and one of them, no doubt, provided the motive power. At three of the four corners of the resulting layout Jacquard mechanisms for operation cards, variable cards, and number cards respectively are indicated. A set of straight racks with the store axes grouped on either side projects from the central circular toothed wheels. The racks are cut short by the edge of the plan, and it is not clear how far they do, in fact, extend. Only 17 axes are shown in the plan. If there were 25 axes altogether--a number that H. P. Babbage considered suitable for a first machine--then the overall length would be increased by 2½ ft. Babbage often speaks of having 1000 axes, but this must be regarded as unrealistic for the technology with which he was working, and more than could in any case be justified by the speed of the mill. Power was presumably to be provided from a steam engine, although Babbage nowhere says so; in his notes he speaks about 'turns of the hand', but he cannot have meant this literally since it is unthinkable that such a large system of machinery could have been set in motion by turning a handle.

CONCLUSIONS AND EVALUATIONS

Babbage began work when mechanical engineering was in a very primitive state and lived through a period when great advances were being made. One cannot help being impressed by his ability (as examplified in his description of Figure 1 printed at the end of the paper) to criticise a design from a practical point of view. This sense of mechanical propriety is further illustrated by his distrust of the use of springs [15]. As far as the Difference Engine was concerned, Babbage chose a practical mechanic of high reputation to be in charge of the construction. It is difficult to know how much Clement contributed to the design. Was it, for example, due to him or Babbage that such a very heavy form of construction was adopted? The difference engine constructed by George and Edward Scheutz, of which a contemporary copy is in the Science Museum, is very much lighter in construction. A model of part of this machine was demonstrated in 1843, and the final version in 1855. It is thus a generation later than Babbage's design for his Difference Engine, and the more modern appearance may be simply a consequence of the progress in mechanical engineering that had taken place in the interval. The piece of the mill of the Analytical Engine constructed by H. P. Babbage after his father's death is also much lighter in construction than the Difference Engine.

The existence of the Scheutz engine proves that the construction of a difference engine was possible given the technology that existed during Babbage's lifetime. George and Edward Scheutz did in fact start with Babbage's own ideas as described by Lardner in a paper published in the *Edinburgh Review* in July 1834. However, the Analytical Engine was much more complex and it is not to be concluded that the technology would have been adequate for that also. As later inventors discovered, there is a world of difference between a device such as a difference engine that operates on a fixed cycle and one that does not. An examination of the piece of the mill just referred to does not make one feel any confidence that the entire system would have worked. At the best it would have been very temperamental and subject to frequent failure. It would also have disillusioned Babbage about machines being incapable of making mistakes. However, the same could be said of the early electronic computers that were built 100 years later. One looks back on them not as fully engineered machines but as representing steps in the development of logical principles and of implementation technology. If, during Babbage's lifetime, the climate of opinion had come round to the point at which a real need for an analytical engine had been felt, then Babbage's work would have provided a headstart as regards logical principles and the first guide to implementation. Years of mechanical development would, however, have been necessary before trouble-free engines could have been produced.

In his book *Passages from the life of a philosopher*, Babbage wrote "If, unwarned by my example, any man shall undertake and shall succeed in really constructing an engine embodying in itself the whole of the executive department of mathematical analysis upon different principles or by simpler mechanical means, I have no fear of leaving my reputation in his charge, for he alone will be fully able to appreciate the nature of my efforts and the value of their results" [Babbage 1864, 450; Morrison and Morrison 1961, 142]. This prediction came literally true. Those of us who lived through the period when modern digital computers were being developed found that later, when we began to read Babbage's published works, we saw at once what he was trying to do and the essential reasonableness of it. In particular we saw the significance of conditional mechanisms and of anticipating carry. We also had a fellow feeling for Babbage in regard to the reactions of the public. We all remember silly questions like, for example, "Pray Mr. Babbage, if you put into the machine wrong figures will the right answers come out?" (Babbage comments: "I am not able rightly to apprehend the kind of confusion of ideas that could give rise to such a question." [Babbage 1864, 67; Morrison and Morrison 1961, 51]). Also, the strange fascination exerted over so many minds by the idea of a machine that can think, and the exasperating irrelevance of this to the designer of a calculating machine [16]. There was, however, one great difference. In Babbage's time everyone accepted Leibnitz's dictum about calculating machines not being for those who deal in vegetables and little fishes [17], and did not in any way foresee the future importance of business data processing. Eckert and Mauchly, on the other hand, the inventors of the first electronic computer, saw this clearly from the outset.

I have long been acquainted with Babbage's published writings but until I began to work on this paper I had not seriously examined his unpublished notebooks. I was by no means prepared to find Babbage living in a world so recognizably like that into which I was plunged 25 years ago. This was by no means the same world as exists today since it was not yet dominated by electronics, and there was still much interest in mechanical computing devices. Babbage's world was purely mechanical. I have found no reference to the use of electricity for any purpose connected with the Analytical Engine.

So intimate is the impression created by Babbage's notebooks that one feels that one has strayed into his laboratory and, while waiting for him to come in, has started to read the papers that are lying about. They are not wholly intelligible, but one is sure that when he does come in he will tell one all about it. Or would he have done? After the Turin episode, there is little evidence that Babbage discussed his detailed ideas with anyone other than his employees, with the one exception of his son. It is clear that in later years a warm bond developed between Henry Babbage and his father, and Henry did all he could after his father's death to carry on his work. At an earlier period, Babbage certainly explained things to Lady Lovelace, but she was a disciple rather than a collaborator. Ever since going through Babbage's notebooks, I have been haunted by the thought of the loneliness of his intellectual life during the period when, as he later tell us, he was working up to 10 or 11 hours a day on the Analytical Engine. Perhaps he found that he could not get people to understand what he was aiming at and, after a while, decided to say little. I have found no references in the notebooks to discussions with other people on points of logical design, although there are one or two references to Whitworth in connection with tools. Babbage sometimes writes of things being agreed, and in one place the word 'proposed' in an ink-written note has been crossed out in pencil and replaced by the word 'agreed' [13]. This perhaps implies that Babbage talked things over with his assistants or with his draughtsman; on the other hand, it could simply be a way of saying that he had decided to adopt a particular suggestion. No correspondence on the technical level of the notebooks with other 'philosophers' of Babbage's own standing has been reported, and if Babbage had been engaged in such correspondence one would have expected to find some reference to it in the notebooks.

If Babbage had realized that his real advances were intellectual and that the principles that he had uncovered were of enduring significance, he might have written a treatise on computer design; he had ample material for such a work and was fully capable of writing it. If he had done so, his position as a computer pioneer in the true sense would have been secure, and as mechanical engineering developed others would have been able to take up his work where he left off. As it is, everything that he discovered had to be re-discovered later.

No-one who has come into contact with Babbage's work can doubt that he was an intellectual giant. He could originate new ideas and develop them without stimulus from outside. His fertile mind kept leading him on towards new horizons. It was partly for this reason and partly because the world was not yet ready for his ideas that his practical achievement in computer development did not match his theoretical advances.

DESCRIPTION OF FIGURES

Figure 1: Part of drawing No. 118 illustrating anticipating carriage. The following description is taken from Babbage Sketchbook IV, 82 ff.

DRAWING 118 FIGS 6 & 7

are sketches made for the purpose of examining a proposed method of an anticipating carriage for both Difference and Analytical Engines.

24 Nov 1842

Each set of figures upon the wheel A *has one tooth a broader than the rest which, when the wheel* A *passes from 8 to 9, acts upon the arm* ^{1}a *and this puts the wire* [the word 'wire' is here used not in our sense but to mean a short metal cylinder used as an interposer] *+9 carried by* ^{2}B *between two adjacent levers, P, in consequence of which lifting the lowest of the two lifts both, or as many as may have the wheels belonging to them standing at 9.*

The same tooth a moves the lever ^{2}B *a second step by passing from 9 to 0 and thus puts the wire +10 under the lever P and its projecting part e over* ^{1}eRW *and therefore when* W *is raised the carrying sector* ^{3}A *is raised into gear with* A *and carriage is effected by the circular motion of* C.

Subtractive carry was to be performed in a similar manner.

As the wheels may stand at 9s or 0s after carriage has been made it was proposed to put ^{2}B *back to its neutral position by stiff*

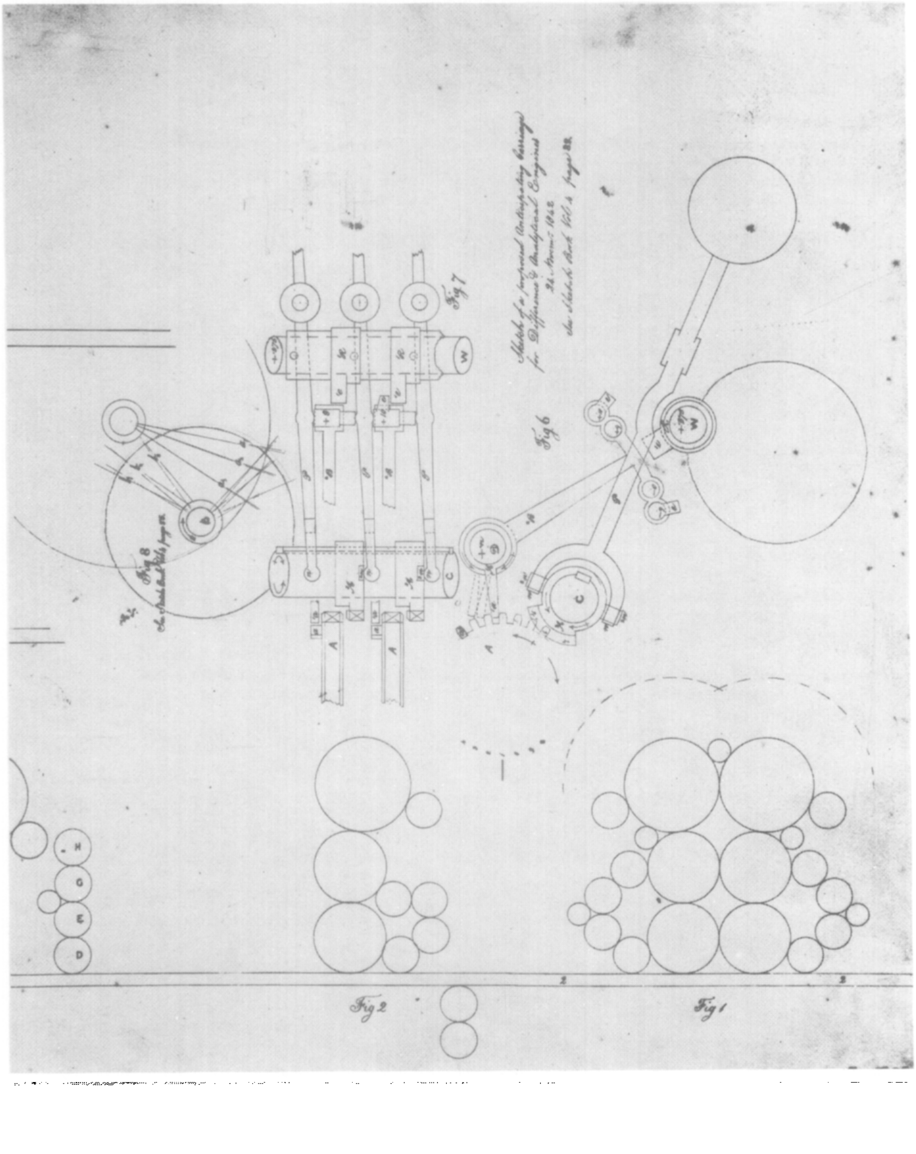

FIGURE 1

friction on its axis D.

To enable ^1a *to move to such a place as would enable it to clear a (for the purpose of changing from addition to subtraction)* ^1A *is intended to move vertically with the axis D while* ^2B *remains at rest between the framing plates.*

Changing from addition to subtraction or vice versa *requires the wheel* A *to be shifted 2 figures and the time required for this and the requisite motions of the arms* ^2B *renders it an undesirable carriage for Analytical Engines.*

It is also defective in this point: that, as ^2B *must be put back by stiff friction as above stated and there is friction between the ends of the wires and the levers P, the one friction is opposed to the other which occasioned it to be rejected for Difference Engines; and lead to its being proposed that for the latter the 9s wire should be moved by cams upon* A *which held it in and out at proper times, and the tens warning should be given by causing a cam upon* A *to move R circularly upon W so as to bring it under some different point of the lever P to that upon which the anticipating wire acted.*

Drawing 118 Fig. 8 is a sketch of a method of putting an arm back to its neutral when it has received warning of 10s carriage but leaving it untouched if warning of 9 only has been given.

about 20 Nov 1842

Warning of 9 moves an arm upon A from a_1 *to* a_2 *which arm moves another upon B from* b_1 *to* b_2*.*

Warning of 10 moves the arm on A from a_2 *to* a_3 *and that on B from* b_2 *to* b_3*.*

To unwarn, B moves down and thus locks with all the arms upon it. It then moves circularly in the direction of the arrow, by which all the arms on A which have received 10s warning are put back, but those which have been only warned for 9s are untouched.

Figure 2: *DRAWING No. 94, 14 AUGUST, 1841*

The storage wheels for two variables, V_4 *and* V_5*, are accommodated on a single vertical axis. The wheels corresponding to* V_5 *are engaged with the rack by moving a shaft carrying a set of pinions upwards, while the wheels corresponding to* V_4 *are engaged by moving the same shaft downwards. Similarly, the shaft which passes through the centre of the storage wheels and imparts the rotation that reduces them to zero during the giving off (that is, reading) operation is engaged with* V_5 *by being moved upwards and with* V_4 *by being moved downwards. The actual rotary motion*

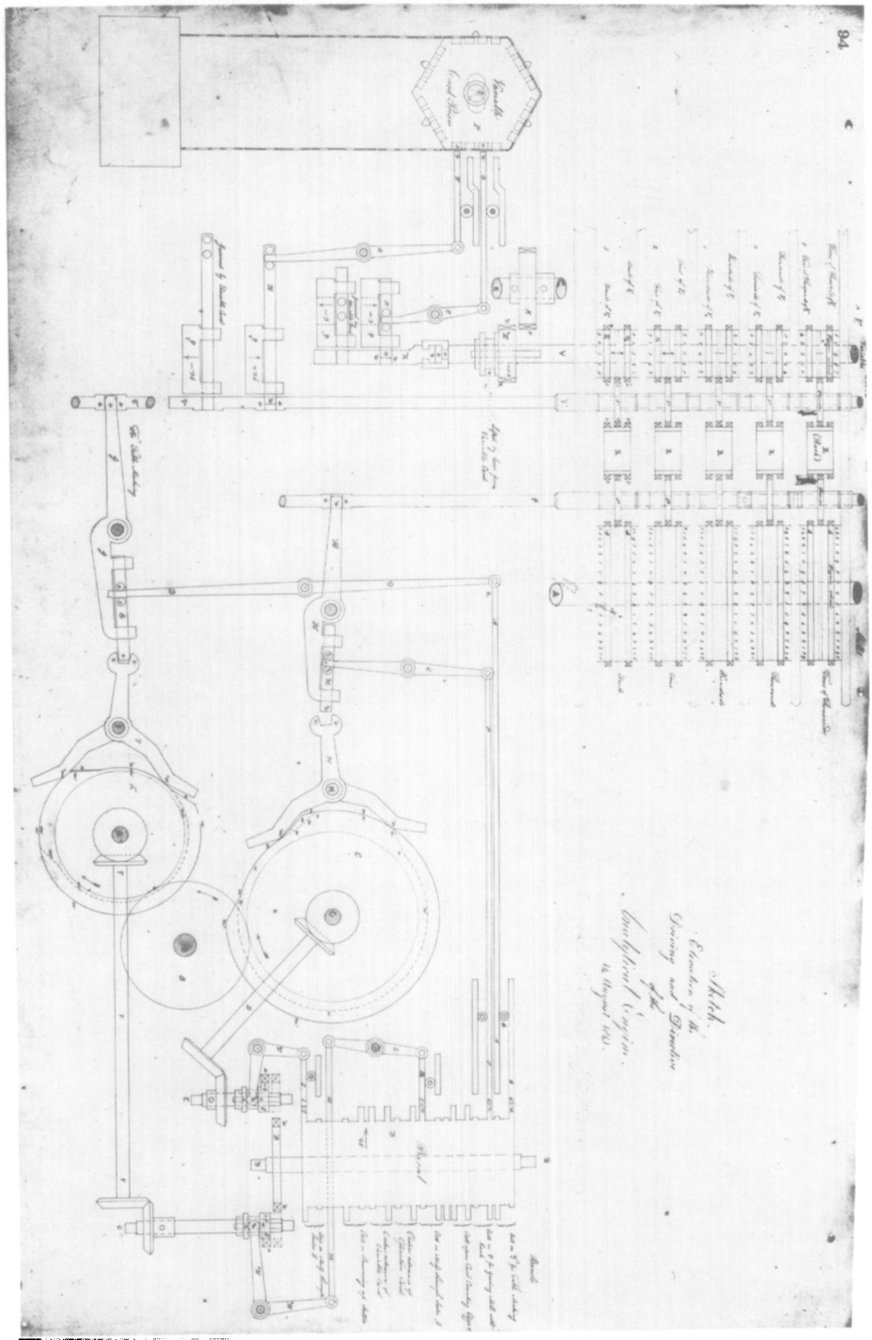

FIGURE 2

is communicated to this shaft via *a pinion that slides in a spline and is moved upwards to engage with a driven pinion at the appropriate time in the operating cycle. A legend referring to the sliding pinion reads "lifted by lever from variable card".*

The Jacquard mechanism is on the left. Two pairs of rods or needles are shown interacting with holes in the card. The two needles in each pair are connected together via *a pinion and consequently move in a push-pull manner. When the top needle is pushed, the mechanism that lifts the shaft through the variable wheels is engaged and when the bottom needle is pushed it is disengaged. The two lower needles similarly engage and disengage the motion that causes the variable wheels to be connected to the racks* [18].

A set of mill wheels is also shown at the top of the diagram. These differ from the variable wheels in having 20 positions, two of which are associated with each decimal digit. It is not clear whether the axis contains two mill variables, one above the other, or whether the upper and lower wheels rigidly fixed together; the mechanism shown for connecting the mill wheels to the rack will only engage the lower wheels. This mechanism is cam driven under the control of a barrel. The two cams and the associated shafts driven by bevel gears all rotate together. One cam controls the up and down motion of shaft carrying pinions that connect the rack to the mill wheels, and the other is used for some unspecified function connnected with making the tables of multiples used in multiplication.

The barrel is shown on the right of the drawing. It acts very much like a card mechanism. It carries fixed stops that interact with pairs of rods connected by pinions. A stop in the top position will cause the tablemaking mechanism to be disengaged, while a stop in the second position will cause this mechanism to be engaged. The next two stops similarly control the pinions that connect the rack with the mill wheels. The way in which the barrel can act on itself, that is, bring about its own rotation, will be noted. A stud in an appropriate position on the barrel, acting through a push rod and an associated linkage, causes a sector sliding in a spline on one of the driven shafts to be moved upwards; when the teeth in this sector come round they engage with those in a gear wheel connected to the barrel. The amount of rotation thus imparted to the barrel will depend on the number of teeth in the sector. Two sets of rods acting on the barrel through different sectors are shown in the drawing.

NOTES

1. A virtually complete collection of the published material relating to Babbage's calculating engines will be found reprinted in [Babbage H P 1889]. This collection was put together by H. P. Babbage in part fulfillment of his father's long-standing intention to publish a full account of the work. A more recent collection of papers relating to Babbage's work has been published by Morrison and Morrison [1961]. Both these volumes include a reprint of Lady Lovelace's translation of Menabrea's paper, together with her notes on it. Lady Lovelace's work is also reprinted in Bowden [1953].

2. An account of Babbage's work on calculating machines based on the published material is given in Wilkes [1956, Ch. 1]. There is an error on pp. 12-13 where it is wrongly stated that a certain number *n* in one of Lady Lovelace's examples is introduced specially for counting.

3. A list of the notebooks (known as Sketchbooks), drawings, and notations in the Science Museum is given in H. P. Babbage [1889, 271 *et seq.*]. A further notebook--the Cambridge notebook --is in the Scientific Periodicals Library (formerly Philosophical Library), Cambridge. The notes are in most cases quite rough and the extracts given here have been edited for punctuation and for consistent use of abbreviations and capital letters.

4. Babbage also turned his attention over the years to *hoarding carriage*, that is, saving the carry digits generated in a long series of additions (for example, those required for a multiplication) and performing the carriage at the end. His first drawing on the subject (No. 57) is dated 4 November 1837. He thought of having two or three counter wheels associated with each stage of the adder so as to be able to accumulate the carry digits for as many as 100 or 1000 additions. See the Cambridge notebook mentioned in note 3, p. 444, 15 November 1857. Babbage does not seem to have observed that, if the carry is allowed to propagate one stage after each addition, then it is only necessary to have storage for one binary digit per stage however long the series of additions may be. He would probably have claimed, however, that by means of anticipatory carriage he could perform the complete carriage in the time required to propagate the carry one stage.

5. "The general view of the directive part was now imagined--barrels with fixed studs corresponding to all the cases [i.e. receive, give off, give off and retain] for each axis were proposed. According as these barrels stood at any particular case so when pushed forwards they lifted [?] the necessary axes to travelling platforms which being raised the circular motions were given by other means at the right times. "These barrels were brought to the right cases by drums with adjustable stops. These adjustments were made from the operations

required by the algebraic formula. And these drums, one of which belonged to each barrel, were called into action by a large drum with adjustable stops which advanced a tooth at each operation.

"Thus the large drum decided when any given operation was to be performed and what quantities were to be concerned in the operation--the small drum acting on the barrels decided the nature of the operation and which of the 4 variables to which they belonged were to be acted upon."

(From an unfinished 'Sketch of the history of the new engine' dated 25 June 1835 to be found at the beginning of Sketchbook XIII.)

6. Babbage estimated that the time required to multiply 50 digits by 50 digits would be about one minute. This he regarded as fast, as the following quotation shows: "Called at the Admiralty when I saw Captain Washington and found a deaf and dumb gentleman, the best accountant they had. When asked the time it would require to multiply 50 figures by 50, he wrote down 'half an hour'." [Babbage Cambridge notebook, 426, 25 June 1861.] Captain (later Rear-Admiral) John Washington, R.N., F.R.S., (1800-1863) was hydrographer to the Navy.

7. Babbage even refers, although not I think with any serious intention of implementing it, to a "plan for breaking off at any part of a series of verticals, of going to an intermediate set, and returning to the next succeeding vertical of the first set." [Babbage Sketchbook V, 390, 1843].

8. "The last vertical of each operation orders the next operation card and its index variable card to advance.

"Each index has had unity subtracted from it previously to putting it on its card, but on the other hand unity has been put upon the index counting apparatus before the index is put upon it so that the true index always exists upon the index card counting apparatus. This is done in order to save time when the indices are all unity.

"After every advance of an operation card, unity is subtracted from the operation index counting apparatus and trial is made whether it runs up. If it do not run up then the same operation card remains and advances the next time. If it run up this orders the turning of a new operation card and also of its index variable card, leaving them both to advance by order of barrel." [Babbage Sketchbook V, 90, 26 March 1842.]

When I first began to study the Sketchbooks I assumed that by 'running up' Babbage meant 'overflow'. The extract just quoted, however, together with those quoted in notes 9 and 12, make it clear that running up occurs when the count has been reduced to zero and not to -1. It is evident that a simple adaptation of the anticipatory carriage mechanism would enable a trial to be made of whether the subtraction of a unit would lead to an overflow without actually completing the subtraction.

9. "The operation cards carry on them indices which represent the number of times the operation is to be repeated. This index is conveyed through sectors to a CCAp. The first vertical of that operation disconnects these sectors from that card counting apparatus. When the card advances again the same index is again transferred to those sectors and they by reducing to zero would give the index to the CCAp if it had not been thus disconnected from them. At each counting off of unity from the CCAp, the card advances until the number on that CCAp is reduced to zero. The CCAp then orders by running up a new operation card to be turned and the index sectors again to be connected with its own wheels.

"In case the operation card is for approximation, the first vertical must put unity on the card counting apparatus and disconnect it from the index sectors, which in this case are to receive the approximating number (a). These sectors must at the same time be connected with the mill or store counting apparatus as the case may require." [Babbage Sketchbook V, 389, March 1843.] The function of the store counting apparatus is not clear.

10. "Plan for operation card giving its index to certain sectors at the same time it gives the barrel an order for an operation.

"If for each of the three digits of which the CCAp consists we have three sectors of 1, 3, 9 teeth, and if the sectors one and three can be reversed, then each digit will require three holes in the cards for the sector and two for the reversing order, so that every operation card if it have 15 holes can put upon the index sectors any number less than a thousand.

"It is now proposed to admit blank variable cards and either blank operation cards or several such cards in succession for one operation. The object is to make the card counting apparatus always convey its orders *through* the operation cards and thus on one hand to save special sectors for enabling the running up of a CCAp to act on the barrels, ["Act on a barrel" is a term of art signifying "cause the barrel to be rotated". The angle of rotation is determined by the number of teeth in a sector. See Figure 2 for an example of how a barrel can act on itself] and on the other hand to save verticals themselves where a postponed order would otherwise become necessary. N.B. A postponed order has usually been executed by a conditional arm or by a double train of verticals, both of which increase the mechanism. This system of double or multiple cards requires no conditional mechanism.

"Owing to the introduction of indices with operation cards the saving in the number of those cards becomes so great that it was thought that the few additional ones might now be admitted. On the other hand, the additional difficulty of putting formulae on to cards was thought to be more than compensated by the saving in the number of cards used." [Babbage Sketchbook V, 455, 9

November 1843].
"Everything relating to the indices and their manipulation must be ordered by *cards*. As, for example: On what CCAp each index is to be put? What index on one CCAp is to be added to or subtracted from any other CCAp? What number is to be subtracted by counting off arms from any and what CCAp? But *when* [doubly underlined in original] these subtractions or additions are to be made must be decided by the vertical of barrel. This will in most cases prevent the necessity of putting n-1 or n-2 as an index instead of the real number n." [Babbage Sketchbook V, 481, 7 December 1843].

11. "Four sectors, capable of being separately put into gear, having 1, 2, 3, 4 teeth respectively, and capable when geared of acting successively, will give all the combinations 1, 2, ..., 10." [Babbage Sketchbook II, 124, 27 May 1836]

12. "To cause the repetition of a group of cards *p* times, let the immediate antecedent card put an index ordering the *number* of repetitions of the subsequent group to be placed upon a counting apparatus. Let the last card of the group order unity to be subtracted from this counting apparatus. After *p* repetitions of the group the CCAp on which *p* has been placed will run up and order the series of cards to be continued or any other group to be backed." [Babbage Sketchbook V, 405, 9 June 1843]

13. "It has hitherto been proposed to have a connection between CCAps and store in order that numbers calculated for indices might be given from there to CCAps. Since it has been agreed [Originally written in ink as *planned* and changed to *agreed* in pencil] to let indices be given by operations cards and also to let those cards direct what CCAps are to receive them, it seems capable of demonstration that no advantage is gained by this connection, and clearly it is desirable to avoid it if only for saving space on the rack.
"For any number less than a thousand can be given by an operation card (which need not order any operation) to any CCAp it may direct. The store could through a variable card only give the same number through the rack. The store could it is true give different numbers at the same turn to several CCAps but such numbers could be given by successive operation cards for the same CCAp, and the few turns lost in this process are quite immaterial in such a vast series of operations." [Babbage Sketchbook V, 457, 9 November 1843]

14. "It is agreed provisionally that the running up of CCAps shall act directly on the barrels and not through the intervention of the cards.
"Because a running up of axes must already exist for other purposes, so arranged that whenever it [*sic*] is acted upon by any running up, one out of many arms must previously have been put into action to determine the thing to be done by that running up." [Babbage Sketchbook V, 532, 20 July 1844]

15. "To have no spring to do work, only retaining springs.' Babbage Sketchbook III, 80]

16. The subject must have come up in Turin, for Menabrea wrote: "... la machine n'est point un être qui pense, mais un simple automate qui agit suivant les lois qu'on lui a tracées." [Menabrea 1842, 358]

17. "Non est facta pro his qui olera aut pisculos vendunt, sed pro observatoriis aut cameris computorum, aut aliis, qui sumptus facile ferunt et multo calculo egent." [Quoted by Lardner 1834, 322 and by Babbage H P 1889, 332; Morrison and Morrison 1961, 219 and 333]

18. In this diagram Babbage shows the use of intermediate pinions for connecting the teeth cut on the variable wheels with the rack. It is more usual, however, for him to imply that the entire axis is raised or lowered to engage the teeth cut on the store wheels directly with the rack.

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Bibliographic Note

Since publication of this paper Professor Wilkes has written two papers on Babbage "How Babbage's dream came true" 1975 *Nature* 257, 541; and "Charles Babbage and the Design of a Control Unit" to be published in the Proceedings of the 1976 Los Alamos Conference on the History of Computing.