CHARLES BABBAGE'S
ANALYTICAL ENGINE
1838

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Abstract. Charles Babbage commenced work on the design of the Analytical Engine in 1834 following the collapse of the project to build the Difference Engine. His ideas evolved rapidly and by 1838 most of the important concepts used in his later designs were established. This paper describes the design of the Analytical Engine as it stood in early 1838, concentrating on the overall functional organisation of the mill (or central processing portion) and the methods generally used for the four basic arithmetic operations of addition, subtraction, multiplication and division. It does not describe the detailed organisation of these functions nor the manner in which the control was arranged by means of "microprogramming". Neither does the paper describe the programming of the Analytical Engine by the user.

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1. Introduction

Charles Babbage commenced work on the design of the Analytical Engine in mid 1834, about a year after the termination of work on the construction of the Difference Engine. His ideas evolved very rapidly and by the end of 1837 the general outline of the design of the Analytical Engine was well established and detailed designs were well advanced. Thereafter work progressed in an evolutionary rather than revolutionary fashion until about 1847 with increased refinement and elaboration of the ideas developed earlier.

In about 1856 Babbage returned to the design of the Analytical Engine with the intention of so simplifying it that it could be constructed at a price within his own means. Work during this phase, which continued until his death in 1871, increasingly emphasised technological considerations and evolved a machine radically different in form to the earlier designs, but not significantly different in conception.

In this paper we will consider the design of the Analytical Engine as it stood in 1838, at which time the essential arithmetic principles were adequately established and before the elaboration and refinement of the design had made it unmanageably complex. A functional description of this model of the Analytical Engine in Babbage's own hand has recently been published in Randell [1975] and a more thorough and detailed technical description is in Bromley [1980].

2. An Overview

Figure 1 shows the general physical arrangement of the Analytical Engine and corresponds closely to a modern functional block diagram. This diagram is from Babbage's original drawing[2] BAB.[A]89* of August 1840. Additional notations have been added for the present use to make the functions of the various parts more evident.

The Analytical Engine is divided into two principal functional parts: the Store in which numbers are held between operations, and the Mill where arithmetic manipulations of numbers taken from the store are performed.

[2] The various manuscript papers describing the Analytical Engine are identified by their catalogue numbers in the technical history and catalogue currently being prepared by this author. Almost all of these are in the archive collection of the Science Museum, London.
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The store is that portion of the apparatus on the rightmost of the figure. Numbers are stored on figure wheels arranged vertically on the figure axes V<1>, V<2>,..., corresponding to the words of storage in a modern computer memory. Each of the figure wheels may rest in any of ten distinct positions and represent thereby any of the decimal digits 0,1,...9. There are forty figure wheels on each axis so numbers of up to forty digits may be stored. This very great precision, equivalent to over 130 bits in a modern computer word, may in part represent an attempt to minimise scaling difficulties arising from the absence of a floating point number representation. Signed numbers are represented in a sign and magnitude system, the topmost or most significant figure wheel designates a positive number if it stands at 0 or any even digit and a negative number if it stands at any odd digit. This representation is very convenient for multiplication and division operations, but causes some complications in addition and subtraction.

Numbers are conveyed to and from the store axes by a system of horizontal racks or toothed bars, one for each digit position, shown extending to the right in the figure. These racks act as a memory data bus. Intermediate gearing, arranged on axes that can be moved vertically through a small distance, enable the figure wheels on each store axis to be engaged or disengaged from the racks. A number is read from the store by first engaging the figure wheels of the appropriate figure axis with the racks and then reducing all of the figure wheels so that they stand at 0 by means of special zeroing lugs provided on the figure wheels. In the process each figure wheel will be moved through a distance proportional to the digit which it originally stored and this motion will be conveyed to the store racks and thence into the mill. Finally the figure wheels are disengaged from the rack and this is restored to its original position ready for the next operation. Numbers are thus fetched from the store by a form of destructive readout which Babbage termed "giving off". At a later date the difficulties of the destructive readout were removed by making it possible to leave the figure wheels engaged with the racks until these were restored to their original position so that the figure wheels were also restored to their original positions. However at the time of the design described this was achieved by a much more awkward process of saving the number on another set of figure wheels in a complement form during the readout and restoring them during another cycle of the store (usually overlapped with a long mill operation such as a multiplication or division).

To store a number on a figure axis the figure wheels are first all set to 0 by a preceeding read operation. Then the figure wheels are engaged with the racks and the racks are also engaged with a set of figure wheels in the mill
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holding the number to be stored. The figure wheels in the mill are reduced to 0 and their motion in the process is conveyed by the racks to the figure wheels of the store axis so that each stands at a digit corresponding to that originally in the mill. Finally the store figure wheels are disengaged from the racks which are restored to their original positions in preparation for the next read or write operation. It is quite possible for a number given off by the mill to be stored simultaneously on several of the store axes.

The mill consists of a number of axes of figure wheels, generally similar to those of the store and corresponding to the registers of a modern computer, arranged around a set of large central wheels. These central wheels act similarly to the rack in conveying numbers from one register to another but, being wheels, have the advantage that at the end of each transfer they do not need to be restored to their initial positions, but may be left where they stand in preparation for the next operation. As a result of this, transfers between registers in the mill are generally faster than transfers to and from the store.

The principal registers in the mill are:

(1) the Ingress axis I, which is used as a buffer register for numbers read from the store into the mill;
(2) the Egress axis "A, which is used as a buffer register for numbers written from the mill into the store, and also to hold the multiplier in multiplication and the quotient in division;
(3) nine Table axes T<1> to T<9>, which hold the corresponding multiples of the multiplicand in multiplication and the divisor in division and are central to the speed-up techniques used for these operations;
(4) two accumulators A and 'A, used in addition and subtraction and jointly to hold a double length number in multiplication and division when A holds the most significant half and is called the Head axis and 'A holds the least significant half and is called the Tail axis;
(5) two special sets of figure wheels F and 'F, used for carry propagation and normally associated with A and 'A respectively;
(6) a third set of carriage figure wheels "F, used in conjunction with "A in addition and subtraction.

The carriage figure wheels "F may also be used in conjunction with the ingress axis I to perform simple additive operations on numbers in the store in parallel with the lengthy multiplication and division operations in the mill. In this case the numbers in the store will be treated in a tens complement representation.

The control of the Analytical Engine was microprogrammed; the words of the microprogram being represented by
vertical rows of studs fixed on the surface of cylinders in something like the manner of the pin cylinders of a barrel organ or music box. The microprograms were termed Barrels by Babbage and the words were termed Verticals. There were generally several barrels in the control of the Analytical Engine which each controlled some portion of the mill apparatus. Each barrel had its own Reducing Apparatus whose function was to control the sequencing between verticals: the conditional and unconditional branching between words of the microprograms. The sequencing of the several barrels was generally independent of one another so that the control had much of the nature of the cooperative execution of distributed microprograms. This arrangement was very sophisticated in both its conception and execution, but made possible a very time efficient utilisation of the apparatus of the mill.

The entire apparatus was driven synchronously from a single shaft corresponding to the clock signal generator in modern computers. The unit of time or minor cycle, the time required to move a figure wheel through a single digit position, was about 0.15 seconds. The major cycle, or register transfer time, was either 15 or 20 units in the mill (2.3 or 3.0 seconds) and 20 units (3.0 seconds) in the store. Signed additions and subtractions could be performed at an effective rate of nearly one every 3 seconds if performed in a lengthy series. Multiplication and division took from one to four minutes depending on the operands.

3. Anticipating Carriage

Transfers between registers within the mill also involved a destructive readout from the source register in the same manner as transfers from the store. To alleviate this difficulty all figure axes within the mill carried two independent sets of figure wheels which could store separate numbers. Each figure axis thus corresponds to a pair of registers, and in the most common usage a number given off from one is retained on the other. A number is repeatedly given off from a register by transferring it backwards and forwards between the two sets of figure wheels. The mechanism is analogous to a register in an electronic computer comprising two sets of simple RS flip flops that act together in a master-slave manner. The mechanism of the Analytical Engine however allowed the two sets of figure wheels on a figure axis to be used independently if so desired.

The apparatus associated with the mill registers is typified by that shown in figure 1 below the Head axis A and sketched in elevation in figure 2. The idler pinions on the axes J and G can be moved vertically to engage the figure wheels on the axis A with the Long Pinions L and S
respectively. These have long toothed segments that extend almost the full height of each cage, the vertical division of all axes into digit units. The long pinions L and S are normally engaged with one another so that by suitable positioning of the transfer pinions J and G a number can be given off by one set of figure wheels of A and transferred via J, L, S, and G to be taken up by the other set of figure wheels. The long pinions also serve as the distributing point for transfers of numbers to or from other parts of the mill. The most important connections are via the pinions O to the central wheels and via the pinions I to the carriage apparatus F.

The long pinions S are also able to be moved a small distance vertically on their axis so that instead of engaging with the long pinion L in the same cage they engage with the long pinion L in the cage above, i.e. corresponding to the next most significant digit position above. This arrangement is shown in figure 2. If now a number is given off by one set of figure wheels on A to be taken up by the other it will in the process be stepped down by one digit position or divided by ten. The effect is identical to division by two by shifting in a binary computer. Since all gearing is reversible a number may be given off by one set of figure wheels on A and transferred in the reverse direction via G, S, L, and J to be taken up by the other set and in the process stepped up to effectively multiply it by ten. Such stepping operations are widely used in multiplication and division and there is further provision for double length quantities to be shifted together between A and 'A, and triple length quantities between A, 'A, and "A.

The above description assumes that the second set of figure wheels on A were initially cleared to zero so that they might correctly take up the quantity given off by the first set. If the figure wheels are not initially zero the effect is that they are further displaced during the transfer so that they will finally stand at the sum of the digit initially stored and of that transferred. However there is no provision for carry propogation from one digit position to the next above if the digit sum exceeds 9.

One of Babbage's greatest achievements was to find a way in which carry propagation could be made through the full length of the forty digit number registers in a single time unit equivalent to that to move a figure wheel through a single digit position. This is far faster than any form of serial carry propagation which would have slowed the machine by a factor of four or five in execution speed. The apparatus, which Babbage called the Anticipating Carriage, is shown in plan in figure 3 and elevation in figure 4.
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The Anticipating Carriage is based around a set of figure wheels, D in figures 3 and 4 corresponding to F in figure 1, generally similar to the figure wheels of the number axes. To add two numbers the carriage figure wheels are first zeroed, and the first addend is transferred to them. This can never cause a carry. The second addend is then transferred to the carriage figure wheels and in the process the digit sums are produced as just described. If any carriage figure wheel passes in the process from 9 to 0, so that a carriage is warned, the arms on axis E are turned by a system of cams and arms to register this fact. Next the axis E is lifted so that in every cage where a carriage has been warned the trident shaped pieces w, called the Fixed Wires, are raised to put into gear the sectors G in the cage above. Finally the sectors G are rotated through one digit position and in the process cause the figure wheel in the cage above that where the carry was generated to be moved forward one digit position to effect the carriage.

The carriage figure wheels carry arms in the ends of which are loose slugs w called the Movable Wires. When the figure wheel stands at 9 the movable wire is interposed between the fixed wire in the cage below and the the fixed wire in this cage. If then there is a carry generated in the cage below, so that the fixed wire is lifted to cause a carry, the interposing movable wire causes the fixed wire in this cage also to be raised to cause a carry in the cage above. Thus the carry from the cage below is propagated by the movable wire into the cage above as well. If several successive figure wheels stand at 9 then a carry can be propagated through the entire group by each movable wire "completing a chain" between successive fixed wires. Since in this case the several fixed wires are all lifted as a unit there is no effective time delay in the carry propagation.

The carriage figure wheels are not normally used as an accumulator. Rather a sum is accumulated on the figure axis A, with every number transferred to these being also transferred to the carriage figure wheels. Then by keeping the various transfer gears engaged during the carry propagation, the reversible action of the gearing will cause the motion of the carriage figure wheels from the carry sectors G to be conveyed also to the figure wheels of A. The figure wheels of A and the carriage figure wheels therefore move together throughout the addition and there is no need for the result to be transferred from the carriage figure wheels at the end of the addition. Indeed by establishing the appropriate gearings the carriage apparatus may be used with any of the registers of the mill.

A transfer between registers of the mill normally occupies 15 units of time, nine of which are required for the transfer of the digits themselves, and the remainder are
required to set up the necessary data paths by movement of the axes of transfer pinions, the locking into place of the figure wheels at the end of the transfer, etc. If a carriage is propagated, the time is increased by a further five units to 20 to allow for the relatively complex motions of the carriage apparatus and because the data paths required during carry propagation are generally different from those during the data transfer. (For example, the source of the number needs to be disconnected during the carry or it will not be left correctly zeroed since the gearing is reversible.)

Subtraction requires the propagation of borrows rather than carries which is easily effected by reversing the motion of the carriage sectors G. However the borrows need to be propagated by figure wheels that stand at 0 rather than 9. To avoid the complexities of an additional set of arms and movable wires on the figure wheels this is achieved by recoding the digit positions on the figure wheels so that the 0 of the subtractive markings corresponds to the 9 of the additive markings. One consequence of this is that addition and subtraction operations can not be readily mixed when the sign and magnitude representation is used. In some situations a tens complement representation of signed numbers was used to alleviate this difficulty.

A carry out of the most significant digit position and into the sign position was commonly used, as in modern binary computers, to alter the flow of control of the microprogram barrels. A carry in such a situation is called a Running Up.

4. Multiplication

With the sign and magnitude representation for numbers used in the store, multiplication is readily reduced to the multiplication of unsigned numbers. The sign of each operand is stripped as each operand is transferred from the ingress axis into the mill, and the sign digits of the two operands are simply added to give the sign of the result, using the parity encoding of even digits to positive numbers and odd digits to negative numbers.

To minimise the time required for multiplication, the operand with the smaller number of significant figures is taken as the multiplier. This is determined by choosing whichever is smaller in numeric magnitude, the test being done by a subtraction and examination of the running up of the carriage apparatus. There are also short exits if either of the operands is zero.

The multiples from 1 to 9 of the multiplicand are then constructed on the table axes \( T^<1> \) to \( T^<9> \). Initially these
are all zero. The multiplicand is given off via the central wheels and added to each, and also to the figure wheels of a carriage apparatus. T<1> is then disconnected from the central wheels. The multiplicand is then given off again via the central wheels and added to each of the remaining table axes as well as to the carriage figure wheels, and the carriages are transferred as well via the central wheels so that T<2> to T<9> all hold twice the multiplicand. T<2> is then disconnected from the central wheels and the process is continued to build up the further multiples of the multiplicand.

During the multiplication proper the multiplier is kept on the egress axis "A and stepped down with each step of the multiplication to supply the multiplier digits in order from the least significant. Each digit of the multiplier is sent to Selecting Apparatus associated with the table axes to select the appropriate multiple of the multiplier to be used as the next partial product. This is transferred via the central wheels to the axes A and 'A which serve as a double length accumulator for the product.

The partially formed product is not shifted in the accumulator registers as the partial products are generated, as is the usual case in binary computers, but rather the table of products of the multiplicand is stepped up in each step to give the appropriate alignment. For this purpose each of the table axes is provided with stepping long pinions, including a wrap around arrangement so that the most significant digit stepped off the top is returned to the bottom in the manner of a cyclic shift. The products are transferred via the central wheels as a single length quantity however, whose least significant digits, produced by the wrap around, correspond to the least significant digit positions of the head (or upper half) of the product, and whose more significant digits correspond to the more significant digit positions of the tail of the product. The appropriate digits are transferred to the figure axes A and 'A via the transfer pinions of the axes 0 and '0 and the long pinions. The transfer pinions 0 and '0 are placed into gear under control of the adjacent Spiral Axes, an arrangement of cams that permits selected pinions only to be placed into gear with the central wheels. Pinions which are not placed into gear convey no motion and therefore correspond to 0 digits. The nett effect is to apportion the digits of the partial products across the head and tail axes as desired.

The timing of these various actions is so contrived that a partial product is selected and added to the product in each major cycle of the mill. The major consequence of this is that the stepping of the digits of the multiplier down off the axis "A leads by one cycle the actual selection
and addition of the partial products. "Pipelining" of operations in this manner is common throughout the Analytical Engine.

Carrys are not propagated in the product with each partial product added. Instead as each partial product is added any carrys, evidenced by the figure wheels of the sum passing from 9 to 0 cause the other figure wheel in the same cage to be advanced by one digit position. The carrys are hoarded in this manner until ten partial products have been accumulated. Then the hoarded carrys are stepped up one cage and added to the product using the full anticipating carriage (for which purpose the carriage figure wheels always receive the same numbers as those accumulating the product). This hoarding carriage is intended to speed up the multiplication by substituting ten short cycles of 15 units and one of 20 units for the anticipating carriage, or a total of 170 units, for ten cycles of the full anticipating carriage, or 200 units. The possible speed gain of 15% is reduced in practice by the number of digits in the multiplier being a multiple of ten and the advantage of the process is dubious, although the mechanism is relatively simple.

The formation and accumulation of partial products is terminated when all of the digits of the multiplier have been exhausted. For this purpose a counting apparatus is set at the start of the multiplication to the number of significant digits in the multiplier. The number of digits is counted in a most ingenious manner using the carriage apparatus 'P in conjunction with the Picking Up Sectors Y. These have 1, 2, 3...40 teeth in the successive cages, and all corresponding to non-zero digits in the multiplier are put into motion so that the output shaft is moved through as many positions as the number of the cage in which the most significant digit lies; this is transferred to the counting apparatus. The count is decreased by one with each step of the multiplication and a consecutive carriage apparatus causes a running up when the count reaches zero. The counting apparatus has two or three decimal digits.

The operands of the multiplication are presumed to both have the same fixed number d of digits following the decimal point. This constant is given to the machine either by a special setting wheel, or may perhaps be read from the memory. It can be manipulated by further counting apparatus, and the Analytical Engine contrives to produce all results with the same fixed number of digits following the decimal point. In the case of multiplication the result will have 2d decimal places and must be stepped down by d places to correctly align the decimal point. This is done at the completion of the multiplication by stepping A, 'A and "A together as a triple length register. The result is a
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correctly aligned double length product in A and 'A with the surplus digits moved out in the stepping on "A. All three parts of the product are stored for possible use in programs for multi-length multiplications.

The time to perform a multiplication includes a fixed overhead for fetching and storing the operands and building the table of multiples (the counting of the digits of the multiplier takes place in parallel with the building of the table, as illustrated in figure 5), together with a component proportional to the number of figures after the decimal point and another proportional to the number of significant digits in the multiplier. But the actual values of the multiplier digits have no effect on the timing as would be the case if repeated addition were used in forming each partial product. In the worst case, where the operands are 40 digit fractions, the time for multiplication is just over four minutes. However a time of 2 minutes would be a more typical average case.

5. Division

Division seems to be an inherently trial and error process. This gave Babbage some initial difficulties, for it meant that the Analytical Engine was required to take different courses of action depending on conditions that arose in the process of its operation. This is in contrast to the operation of the Difference Engine, which is fixed and independent of the particular calculation being made. It was from the study of the problem of implementing division that Babbage was led to the idea of operations conditionally determined by the occurrence of a running up, and thence quite quickly to the barrels and the conditional transfers within them as a flexible means for implementing the elaborate algorithms that arose. Indeed his use of punched cards for the main control of the Analytical Engine originated as a more convenient medium than the hierarchy of barrels that he originally envisaged for the purpose.

The division uses a restoring technique and, by using a pre-constructed table of multiples of the divisor, generates one digit of the quotient in each step of the division. The divisor is fetched first from the store and tested if zero in which case the division is aborted. The multiples from 1 to 9 of the divisor are then constructed on the table axes in the same manner as in multiplication. As each multiple is constructed the two most significant digits of the multiple are selected off by the axes R and R<1> under control of a spiral axis set to the number of significant digits in the divisor. These two most significant digits of each multiple are stored on special figure wheels on the table axes, and are used by the selecting apparatus during the division to estimate the successive digits of the quotient by
simultaneously comparing each pair with the two most significant digits of the remainder at each step.

Since the result of a multiplication may be a triple length quantity the dividend is supposed to have the same form. This is read from the store to the axes A, 'A, "A and the number of significant digits is determined. Before the division is commenced the most significant digits of the dividend are aligned with those of the divisor by stepping the dividend up or down an appropriate amount. This is done because stepping is faster than generating leading zero digits in the quotient. During the division the dividend-remainder is regarded as only a double length quantity and some digits of the remainder may be lost.

Each step of the division commences with the dividend-remainder on the head and tail axes being stepped up by one digit position and in the process the two most significant digits of the remainder are selected by the axes R and R<1> and subtracted from the two most significant digits of each multiple of the divisor on the special wheels of the table axes. By examining the running-up which occurs in each of these subtractions a trial quotient digit is selected as the largest multiple whose first two digits are less than or equal to those of the remainder. This trial quotient digit will either be correct or one too large. In a second cycle the special wheels on the table axes are restored to their original values, the trial quotient digit is moved to a special figure wheel on the axis "A, and the selected multiple of the divisor is subtracted from the remainder on the head axis A. If the subtraction results in a running-up the selected quotient digit was too large and in an additional cycle the quotient digit on "A is reduced by one and the divisor is added to the remainder (by subtracting its complement as addition and subtraction cannot be mixed with the carriage apparatus). Finally the quotient digit is moved to the units figure wheel of "A as the partial quotient already there is stepped up one cage. This is done concurrently with the first cycle of the next step of the division, so each step takes two cycles normally or three if the trial quotient digit was too large. In practice the division is further complicated by the movement of the quantities in the mill between the two sets of figure wheels on each axis. This is illustrated by the partial flowchart of division in figure 6.

The number of steps in the division is chosen so that the final quotient and the remainder are both correctly aligned with respect to the position of the decimal point without further stepping. These results are given off to the store at the termination of the division.
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It is possible to perform both multiplication and division to less than the full number of significant figures in the result. These approximative multiplication and division may take considerably less time than the normal operations and are intended for situations, such as the generation of square roots by iterative methods, where only a limited precision is required in the initial stages of a calculation. Aside from the counting of the number of steps involved these operations require a somewhat different handling of the multiplier and quotient on the axis "A". For this purpose the axis "R" and its corresponding spiral axis allow digits to be moved to or from any selected digit position.

6. Signed Addition

Although the sign and magnitude representation for numbers is most convenient for multiplication and division, it is far less convenient for addition and subtraction since the operation to be performed depends on the actual signs of the operands. Each addend is considered in the Analytical Engine to have two signs: an Algebraic sign indicating whether an operand is to be added or subtracted, and an Accidental sign indicating whether the operand when fetched from the store was positive or negative. These are combined to give an effective sign as the operand is fetched from the store. The sign figure wheel of the ingress axis is first set to an odd or even value dependent on the algebraic sign and the accidental sign of the operand is added to this as it is fetched from the store. The resultant sign indicates whether the magnitude read from the store is to be added to or subtracted from the total.

Babbage, as do most modern computer designers, alleviated the difficulties of the sign and magnitude number representation by using a complement number system representation for partial sums within the mill. The actual accumulation of the total is complicated by the fact that the carriage apparatus cannot be used for mixed additions and subtractions as one requires carriage propagation by 9s and the other borrows propagation by 0s; this being achieved with one set of movable wires by a recoding of the digit positions on the carriage figure wheels. This is overcome by using the head axis A to accumulate the total in conjunction with two sets of carriage apparatus: 'F' is used for addition with carry propagation by the 9s; F is used for subtraction with borrow propagation by the 0s. The figure wheels of A, 'F and F are all effectively locked to move together and unwanted carries warned on F in addition and 'F in subtraction are simply ignored. Running-up from the most significant digit position of the accumulated total into the sign position is used to keep track of the sign of the total, but for this reason no carry or overflow indication is
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available. Negative results are converted from the complement back to the sign and magnitude representation upon transfer to the egress axis "A for storage. The carriage apparatus "F is used for this.

There was no residual storage in the mill of the Analytical Engine equivalent to that provided by registers in a modern computer. It would be inefficient in time therefore if addition and subtraction were implemented only as binary operations, as in many instances it would be necessary to fetch from the store a result just immediately stored there. Instead the Analytical Engine could sum a number of operands as a single operation and the residual storage of partial sums was therefore implicit rather than explicit. Further, it was possible to store any of the intermediate results. To make this arrangement speed efficient the functions of the various parts of the mill were elaborately pipelined as indicated by the examples in figure 7. The control of this was by means of a series of distributed microprogram barrels whose internal sequences were effectively independent of one another.

7. Acknowledgement

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8. Bibliography


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Figure Captions

Figure 1. General arrangement of the Analytical Engine plan 25 (BAB.[A]89*, 6 August 1840). This drawing is somewhat later than the plan discussed in this paper but the differences are minor. Versions of this plan and the anticipating carriage were published by H.P. Babbage from lithographs prepared by Charles Babbage. (Crown copyright, Science Museum, London.)

Figure 2. Opened out elevation drawing showing the arrangement of the long pinions when stepping and in normal transfers. The axes are arranged in a group so that the axis A on the right of the figure is the same as that on the left. Transfers in order to the right in the figure result in a stepping down, whilst a transfer to the left results in a stepping up. (BAB.[A]51, 31 August 1837.)

Figure 3. Plan of the Anticipating Carriage together with some auxiliary apparatus used in counting the number of significant digits in a number (BAB.[M]11, 4 December 1836). Some details of the arrangement had been altered by the time of the plan discussed in this paper, but the principles are unchanged. (Crown copyright, Science Museum, London.)

Figure 4. Elevation drawing of the Anticipating Carriage (BAB.[M]13, 4 December 1836). The fixed wires are the trident shaped pieces w and the interposing movable wires are the loose slugs 'w. (Crown copyright, Science Museum, London.)

Figure 5. Major steps in multiplication, illustrating some of the concurrency of operations in the mill. In this example the multiplier has five significant digits and the machine is set for two decimal places in all numbers.

Figure 6. Copy of portion of Babbage's original flowchart or "Notation of Directive" of division (BAB.[F]96/1, 18 July 1838). The doubled loop, with dual entry points and exits, arises from the possibility of the dividend-remainder being on either set of figure wheels of the head axis A as a result of the stepping to align it with the divisor. Step 1 (or 3) corresponds to the stepping up of the remainder and determination of the trial quotient digit. Step 2 (4) is the subtraction to form the new remainder. Step z ('z) is the restoring addition of the divisor if the trial quotient digit is too large and the subtraction left a negative remainder. Step 3 (1) corresponds to the movement of the quotient digit into the final quotient.
Figure 7. Pipelining of transfers within the mill during streamed addition operations. In the case where intermediate results are given off to the store the store racks are the limiting resource and are kept, so far as possible, fully utilised.
Figure 5

Turn

1
2
3
4
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9
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11
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13
14
15
16
17
18
19
20
21
22
23
24

Fetch
Operands
Transfer operands into mill
Select smaller as multiplier

1

Build

table
do
digits in
digits in

of

multiplies

multiplier

and

prepare

Form

of

multiplicand

prepare

counters

"Prepared Multiplier"

Select

Select

partial products

partial products

Accumulate

Add hoarded carriage

Step down product to

align decimal point

Store three part product