UNIVERSITÄT TÜBINGEN

FESTKOLLOQUIUM - 2 NOVEMBER 1973

# CHARLES BABBAGE AND HIS MACHINE

by
J Howlett
Atlas Computer Laboratory
Science Research Council
Chilton, Didcot Berkshire

Very few people, even in England, knew anything about Charles Babbage until quite recently. He lived through most of the 19th century, his life was most active and vigorous and he wrote and published many books and papers on an astonishingly wide variety of subjects. He was brilliantly clever. But his work became almost completely unknown until the late 1940's when some of the people working with what was then a very new device, the electronic digital computer, read his books and papers and found that he had thought out nearly all the principles of an automatic, general-purpose digital computer over 100 years ago; and had made a detailed design for such a machine and had tried, unsuccessfully, to build it. In fact, he spent a great deal of his life, and money, on two machines, which he called the Difference Engine and the Analytical Engine respectively; it is the second which was the forerunner of the modern computer.

## BABBAGE THE MAN

Babbage was born in Devonshire, in South-West England, in 1791; his father was a banker and he lived the life of a rich, eccentric English gentleman who travelled widely and was always on equal terms everywhere in the best society. He was already deeply interested in mathematics when he was quite young and went to Cambridge in 1810, taking a first-class degree in 1814. He published several mathematical papers during 1815 to 1822 and, with two distinguished friends who had been undergraduates with him, Herschel and Peacock, he worked hard to raise the standard of mathematics in England, which was very low at that time. In 1828, although he was not then connected with the university, he was elected to its most distinguished Chair of Mathematics: the Lucasian Chair, which had been held by Newton. He resigned in 1839; in all the 11 years as Professor he never lived in Cambridge or gave a single lecture - probably a world record.

Babbage's interest in calculating machines seems to date from his undergraduate days, around 1812-1813. He started to work on his first machine, the Difference Engine, in 1823 and was forming his first ideas on the much more complex Analytical Engine in 1833; and although he had many other interests, his life was dominated by these machine projects - from then until his death in 1871. I shall say more about his machines later; now I want to say a little about Babbage as a person and about his other work.

He was undoubtedly a most remarkable man. He was interested in, and curious about, practically everything, and especially about any kind of machinery. He had a very quick and agile mind, seemed able to understand everything down to the smallest technical detail and to hold a vast amount of information in his memory. At the same time he was thoroughly original and could always make a personal and fresh approach to any problem. All this comes out clearly in his autobiography, "Passages from the Life of a Philosopher", which he published in 1864 and which was reprinted by Dawsons of London in 1968. It is fascinating reading - but parts are tedious: one sees very clearly that whilst Babbage could be very good and stimulating company, he could also be very obsessive. The chapter headings show something of the scope of his interests; there are 4 dealing with his calculating machines, and from the whole set of 36, here are a few:

IX Of the Mechanical Notation
XIV Recollections of Laplace, Biot, and Humboldt
XVIII Picking Locks and Deciphering
XXV Railways
XXIX Miracles
XXXIII The Author's Contribution to Human Knowledge

The book contains a list of his 80 published papers, and the range is remarkable. Here are a few:

"Demonstration of a Theorem relating to Prime Numbers"

"On the Proportion of Letters Occurring in Various Languages", in a letter to M Quetelet.

"Economy of Manufactures and Machinery". 8vo. 1832.

"On the Statistics of Light-houses". Compte Rendu des Traveaux du Congres General, Bruxelles, Sept. 1853.

"On the Action of Ocean-currents in the Formation of the Strata of the Earth".

"Passages from the Life of a Philosopher" is a very quotable book; I could easily use up all my time and space in quoting selections from it. Let me give just 3, none of which concern Babbage's main work but which I think show several different sides of his character very clearly.

First, the trained mind of the true scientist. Whilst he was staying in Naples in 1828 he decided to climb Vesuvius, which was then moderately active, and to descend into the crater and if possible to observe the movement of the lava in the active region. He gives, incidentally, a splended picture of the rich English traveller: "As I wished to see as much as possible, I made arrangements to economize my strength by using horses or mules to carry me wherever they could go. Where they could not carry me, as for instance, up the steep slope of the cone of ashes, I employed men to convey me in a chair". His account - too long to quote - is quite dramatic. He descended into the main crater, an extensive oval plain about 500 feet below the top of the ridge, covered with a pattern of intersecting cracks in the rock and with a small subsidiary active crater near one part of the edge. He had with him a barometer, a sextant, several thermometers and a measuring tape - not to mention a flask of Irish whiskey.

He surveyed the area and timed the intervals between successive eruptions from the active crater, finding these to be reasonably constant at about 15 minutes. He recorded all his information in a note-book and made a detailed plan of action in which he would approach the edge of the crater along a definite line and could safely watch the interior for 6 minutes before he must retreat to escape the next eruption. It all worked out perfectly, and he had sufficient faith in his timings not to retreat when he saw a large bubble forming and growing in the red-hot liquid lava - it was not yet time for the next eruption.

The second shows how he could not resist recording what I think we must class as trivialities. In his chapter on "Hints for Travellers" he writes at one point: "One of the most useful accomplishments for a philosophical traveller with which I am acquainted, I learned from a workman, who taught me how to punch a hole in a sheet of glass without making a crack in it". He goes on to say quite a lot about this: it seems to have been one of his favourite party tricks.

The third illustrates how he could immediately start to elaborate a new idea. In the chapter - "Further Contributions to Human Knowledge" he makes a short but penetrating study of games of skill in which he sees the possibility of applying his Analytical Engine (ie, a computer) to game-playing. He analyses noughts-and-crosses (which he calls tit-tat-to) in detail, sees that there is always a winning strategy and "I therefore easily sketched out mechanism by which such an automaton could be guided" - ie, he designed a machine to play the game. He then thought that he might turn the idea into an entertainment for which people would pay, and so make money to spend on building the Analytical Engine. He goes on: "It occurred to me that if an automaton were made to play this game, it might be surrounded with such attractive circumstances that a very popular and profitable exhibition might be produced. I imagined that the machine might consist of the figures of two children playing against each other, accompanied by a lamb and a cock. That the child who won the game might clap his hands whilst the cock was crowing, after which, that child who was beaten might cry and wring his hands whilst the lamb began bleating". Fortunately, a few inquiries showed him that there was no money to be made from this kind of display and he dropped the idea.

THE DIFFERENCE ENGINE

Babbage was led to design this machine by his thoughts on mathematical tables and on the great amount of human labour which went into the calculation of these. The theoretical basis of the machine is a few simple results from what we now call the Calculus of Finite Differences. First, if we evaluate a polynomial function at equal intervals of the argument, then write down the differences between consecutive values, then the corresponding differences of this set of numbers, and so on, we arrive at some stage at a set of constant numbers. Thus if $f(x) = x^3 + 2x + 1$ we have:

| x | f(x) | | | |
|---|---|---|---|---|
| 0 | 1 | | | |
| | | 3 | | |
| 1 | 4 | | 6 | |
| | | 9 | | 6 |
| 2 | 13 | | 12 | |
| | | 21 | | 6 |
| 3 | 34 | | 18 | |
| | | 39 | | 6 |
| 4 | 73 | | 24 | |
| | | 63 | | 6 |
| 5 | 136 | | 30 | |
| | | 93 | | (6) |
| 6 | 229 | | (36) | |
| | | (129) | | |
| 7 | (358) | | | |

The theorem is that the <u>n</u>th differences of a polynomial of degree <u>n</u> are constant; here the polynomial is of degree 3 and the $3^{rd}$ differences are all equal to 6. Having calculated the function for a few values, we can now use this knowledge to extend the table as far as we wish simply by successive additions - that is, no multiplications: the rule is simply that if $c = a - b$, then $a = b + c$. Thus having calculated $f(x) = x^3 + 2x + 1$ and its differences as far as $x = 6$, as in the table, we get for the next line of differences:

$$36 = 30 + 6, \quad 129 = 93 + 36, \quad \text{and } (7) = 229 + 129 = 358,$$

and so on.

Further, by means of quite simple formulae (called Interpolation Formulae) we can use the table of differences to calculate values between the tabulated values, for example to form a whole new table at a finer interval, say 0.1 in x in place of the original interval of 1. And finally, if the function is not a polynomial - log x say - differencing will lead, not to a constant but to a set of values which are small in comparison with the function values and we can use the interpolation formulae to calculate intermediate values which, whilst they are approximate in the strict sense, can be guaranteed not to be in error by more than some stated (and small) amount. This use of interpolation is not of any importance for simple functions like $x^3 + 2x + 1$, but for complicated mathematical functions, or for tables used in navigation such as the positions of the moon or certain stars at all times and dates, the direct calculation is most laborious and interpolation is well worth while - even, in many cases, with modern high speed computers.

The purpose of the Difference Engine was to perform these operations - differencing a table, extending a table by additions of difference and interpolation - entering automatically. Babbage of course lived before any kind of electrical or electronic engineering was known and his machine could only be mechanical. The basic principle was to represent a single decimal digit (ie, 0 to 9) by the position of a gear wheel which had 10 teeth; and a number of, say, 6 digits (ie, 0 to 999,999) by a group of such wheels - we may call such a group a register. It is clear that the action of the machine must consist of sequences of additions between registers and that there must be means for setting up cycles of operations (such as the sequence of additions which are required in going from the constant 3$^{rd}$ difference to the next value in the example) and for repeating these. Babbage foresaw every need and designed everything in the greatest of detail, including a means for automatically producing stereo-plates from which the results could be printed, so that no hand-copying should be needed. He obtained the support of the British Government of his day and started to build the machine in 1823, expecting to finish it in 3 or 4 years. The project, however, proved far more difficult than Babbage or anyone else had expected. Mechanical engineering was then in an almost primitive state compared to what we have now; the precision which was necessary if the machine was to work satisfactorily was unobtainable and Babbage had to start by designing and making tools with which the gears and other parts of his machine could be produced with the accuracy which was required. Also, and characteristically, he started with a plan for a machine on far too large a scale - it was to work with numbers with up to 20 decimal digits and with differences up to the 6$^{th}$ order - and this strained the technology of the day beyond what it would bear.

Work on the building of the machine stopped in 1833. After many delays, discussions and argument the government finally withdrew its support in 1842, having spent £17,000 of public money on the project - probably equivalent to about £300,000 (DM.20M) to-day. Babbage had spent about the same amount from his private fortune. Very little of the machine was actually built. There is a very small part in the Science Museum in London, a drawing of which appears in "Passages from the Life of a Philosopher", with the following sad legend:

> "It was commenced 1823
> This portion put together 1833
> The construction abandoned 1842
> This plate was printed June, 1853
> This portion was in the Exhibition 1862".

Ironically, a working machine <u>was</u> made based on Babbage's design. A Swedish printer, P G Scheutz (1785 - 1873) read about Babbage's machine in 1834 and with his son Edward built a small prototype. Much later, in 1851, they got the support of the Swedish Academy and money to build a larger machine and in 1853, having had much help and advice from Babbage himself, they had completed a machine which worked with 14-digit numbers and $4^{th}$-- order differences. The final realisation of Babbage's ideas for the Difference Engine came in the 1940's with the electro-mechanical accounting machines; these are still in use, but are being displaced by small computers. The National machine, for example, has been used very extensively for construction of tables in exactly the way which Babbage had described more than 100 years previously.

THE ANALYTICAL ENGINE

In 1833, when he was in such difficulties in the building of his Difference Engine, Babbage had his great visionary idea: the fully automatic, completely general calculating machine which he called the Analytical Engine. In fact he never built more than a few fragments of this, but this does not detract from the greatness of his vision. It is unlikely that anyone could have built the machine with the technology of the day - it would have been far more demanding than the Difference Engine - and it is the concept which ensures his place in history. The Analytical Engine was to be able to perform any calculation, however long and complex. It was to consist of the following parts:

(i) A store, or set of registers in which numbers could be held.
(ii) A unit which could perform arithmetical operations on numbers put into it: Babbage called this the mill.
(iii) A unit which would take numbers from the store, cause the mill to operate on them and return the results to the store, all as required to carry out the successive steps in the calculation: we can call this the control unit.
(iv) Means for putting numbers and instructions defining the sequence of operations into the machine, and for getting out the results - input/output units, in fact.

This is almost exactly the description of a modern digital computer. Babbage also saw that:

(a) any calculation can be broken down into a sequence of additions, subtractions, multiplications and divisions; so that the mill can be built so that it can do only these 4 basic operations,
(b) the course of a calculation may depend on the result obtained at some intermediate stage - for example, solving an algebraic equation by a purely numerical process - and this cannot be predicted at the start; so the control unit must have some means for changing its sequence of instructions, according to the result obtained at some stage. In fact, Babbage saw that the decision to change course or not could always be made to depend on whether the number in a specified register was positive or negative.

This last is known now as "conditional transfer of control" and is quite fundamental: no machine could be truly automatic without it, for everything would have to be foreseen at the start of the calculation. Babbage saw also that the same principle could be used to cause a cycle of operations to be repeated any chosen number of times.

Again the machine was to be entirely mechanical; as in the Difference Engine a register would be a group of toothed wheels and Babbage planned for 1000 registers, each made up of 50 wheels - that is, each could hold a number of 50 decimal digits. He was clearly aware of the need for high precision in long calculations, but 50 decimals is high even by present-day standards.

The most striking and original feature of the Analytical Engine is the concept of the control unit - nothing like this had ever been proposed before. Babbage thought it out complete with a detailed mechanism, which was based on the principle of the Jacquard loom: it seems likely that he got the idea as a result of seeing one of these machines at work. J M Jacquard invented in 1805 a means for the control of a loom which enabled complex patterns to be woven automatically. The problem is to select, for each successive row of the material which is being woven, the warp threads which have to be raised before the shuttle goes across the material between the warp and the weft. This can be done well enough by hand for plain material and simple patterns - and of course has been done by hand for thousands of years - but becomes almost impossible in the case of complicated patterns. Jacquard's idea was to make this selection by means of a card in which a hole could be punched in a position corresponding to the end of each of the rods which moved the warp threads: a rod could move through a hole if one was punched in its position, if there was no hole it could not. Thus any selection could be moved and in order to produce any pattern in the cloth automatically all that one had to do was to decide in advance which threads had to be moved at each row and punch a series of cards with holes in the corresponding positions. In modern terms, the pattern to be woven is coded by the pattern of holes in the cards. Jacquard's invention was an immediate and very great success and revolutionised the weaving industry.

Babbage saw that this concept of coding - although he never used the term - was of fundamental importance and could be used to control any mechanism; in particular, that it could control the sequence of operations in his Analytical Engine. To use the modern term again, the sequence of patterns of holes in the cards represented the program for the calculation. Again characteristically, Babbage worked it all out in great detail and produced engineers' drawings from which, in principle, the machine could have been built. Further, he foresaw the possibility for such things as "library" packs of cards for frequently used programs or numerical tables (eg, logarithms). He said explicity that experience would be needed before one could decide whether it was better to get the value of a particular function from a table or to calculate it afresh by a library program whenever it was needed.

The most detailed available account of the Analytical Engine is one which was based on a series of lectures which he gave in Turin in 1840. L F Menabrea - an army officer who later became a General under Garibaldi, wrote a very full description of the principals of the machine, with examples of how it could be applied. This was later translated by a very remarkable woman, Ada Augusta, Countess of Lovelace, the daughter of the poet Byron; she had many accomplishments and in particular was a good mathematician - a most uncommon ability in a woman at that time. She obviously understood the principles of the machine very well indeed - probably as well as Babbage himself. She herself added very extensive and detailed notes to her translation of Menabrea's paper, which in total are longer than the paper itself; in one of these she gives what we should now call the program for computing the Bernoulli numbers. One of the most significant statements which she, or anyone else, made about the machine was that "it can do only what we know how to order it to do". Her translation and notes are reproduced in full in the book "Faster than Thought" by B V Bowden (now Lord Bowden), and also "Charles Babbage and his Calculating Engines" by P and E Morrison.

The more one reads about the Analytical Engine, the more one is struck by Babbage's foresight and by his grasp of both the broad concept and the fine details. But it remained only a concept. He made many attempts to get Government support but never succeeded. He spent a great deal of his own time, effort and money in trying to build it, but made only a few fragments. His son, H P Babbage, succeeded in building a small part of the mill after Babbage had died, and this, like the part of the Difference Engine, is in the Science Museum in London. There is a tendency to blame the Government of Babbage's day for being too timid and unimaginative to give him support. I think that is unfair: the ideas were too new for their importance to be appreciated at the time, and there was no obvious and pressing national need for the machine. As I said before, it was too much for the technology of the day, and even if it had been built - a purely mechanical device - it would almost certainly have proved too slow to be of real value - Babbage was predicting a time of one minute for a multiplication. Finally, Babbage was not an easy man to deal with. His mind was too active, and he was always producing new ideas. This had the disastrous result that he would abandon a piece of construction before it was finished, because he could see a better way to do it - to use the modern term once again, he did not realise the importance of freezing the design. He was undoubtedly embittered when he died in 1871; it was his misfortune that in so many ways he was a century ahead of his time.

## REFERENCES


1. Babbage C
   "Passages from the Life of a Philosopher"
   London : Longman : 1864
   re-printed London : Dawson : 1968,

2. Bowden B V
   "Faster than Thought"
   London : Pitman : 1953,

3. Goldstine H H
   "The Computer from Pascal to von Neumann"
   Princeton : University Press : 1972,

4. Morrison E and Morrison P
   "Charles Babbage and his Calculating Engines"
   New York : Dover : 1961,

5. Moseley M
   "Irascible Genius, A Life of Charles Babbage, Inventor"
   London : Hutchinson : 1964,

6. Wilkes M V
   "Automatic Digital Computers"
   London : Methuen : 1956.