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THE ORIGINS OF DIGITAL COMPUTERS

Selected Papers

Edited by Brian Randell

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The Origins of Digital Computers
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The two drawings of Babbage's Analytical Engine given in Chapter II are reproduced by courtesy of the Science Museum, London.

Chapter

Introduction

I

A mere chronology of inventions relating directly to the mechanisation of digital calculation starting, say, with NAPIER or PASCAL, can give an entirely misleading view of the origins of computers. In some cases a particular step forward can be seen to have been directly influenced by knowledge of the efforts of previous pioneers, but in many cases no such evidence is readily discernable. More importantly, such a chronology tends to obscure the role played by other less directly related events, for example, improvements in technology, and changes in governmental and public attitudes, such as occurred at the onset of World War II when vast sums of money were made available for computer development [1]. A proper treatment of the development of the digital computer is therefore very much a task for an historian of science. In this book only the briefest of introductions have been provided to each of the subsequent chapters, in a modest attempt to put the work described in the original accounts that form the bulk of the text into perspective.

As always, one of the difficulties of discussing the origins of an invention is to know where to start and what to include. In the case of the digital computer the work of CHARLES BABBAGE, which far surpassed all that had gone before, provides a very appropriate starting point. However, even then, in order to appreciate his work more adequately, it is appropriate to discuss at least briefly the development of early calculating machines and sequence-control mechanisms. The present chapter is therefore in the main concerned with these two topics. Chapter 2 covers BABBAGE's Analytical Engine, and also the efforts of the people who consciously and deliberately carried on BABBAGE's work on the design of program-controlled calculating machines. The next chapter concerns the development of punched card tabulating machines, starting with HOLLERITH's original devices designed for the 1890 U.S. National Census. The remaining chapters all centre on much more modern developments, marginally the earliest of which is the work by KONRAD ZUSE in Germany, described in Chapter 4. The collaboration between HOWARD AIKEN and IBM which led to the development of the Harvard Mark I is described in Chapter 5, whilst the series of relay computers built at Bell Telephone Laboratories are the subject of Chapter 6. Chapter 7 describes various electronic calculating devices, culminating in ENIAC, the first general-purpose electronic computer. Finally Chapter 8 covers the development of the stored program concept starting with EDVAC and ending with EDSAC, the first practical stored program computer to become operational.

Mechanical Digital Calculation

The idea of using a train of gear wheels linked so that each time one wheel completes a rotation the next wheel turns so as to record the 'carry' of a single unit is a very ancient one indeed, and even appears in the writings of HERO of Alexandria [2]. It was apparently not until the early 17th century that the idea arose of using such a gear train to build an adding machine. Until recently it had been generally accepted that BLAISE PASCAL, the renowned French scientist and philosopher, was the first person to build such a device, but it is now believed that he was preceded by the astronomer WILHELM SCHICKARD of Tübingen [3].

Our knowledge of SCHICKARD's "calculating clock" derives from a description and drawings that he sent to JOHANNES KEPLER in 1624. From these it can be seen that the machine incorporated not only a train of gear wheels which served as an accumulator, but also a separate set of unconnected wheels forming a register in which results could be (manually) recorded, and a set of six cylinders on which were engraved multiplication tables, after the style of NAPIER's rods. According to SCHICKARD his machine functioned well but shortly after it had been completed it was destroyed by fire, whereupon the project was abandoned.

PASCAL started work on the design of an adding machine in order to assist his father, a French government official, with his book-keeping calculations [4]. After many unsuccessful attempts, in 1642 at the age of nineteen he arrived at the basic design of his machine. By 1645 he had completed his machine, for which he was granted letters patent. Quite a few further machines were built to his design and sold, several of which still exist, but their unreliability meant that they were treated as objects of scientific curiosity rather than as practical calculating machines.

In the years that followed many further attempts were made to build practical calculating machines, by people such as MORLAND, LEIBNIZ, GRILLET, POLENI, LEUPOLD, and many others [5]. Of these perhaps the most noteworthy was GOTTFRIED LEIBNIZ (1646—1716), the great philosopher and mathematician, whose machine later formed the basis for the first successful calculator [6]. The major advance over PASCAL's machine was that a multi-digit number could be set up beforehand and then added to the number already in the accumulator by turning a handle. Thus multiplication could be performed by repeated turns of the handle, and by shifting the position of the carriage relative to the accumulator, whereas with PASCAL's machine it was necessary for the number which was to be multiplied to be set up repeatedly, digit by digit.

LEIBNIZ designed his machine in 1671 but it was not constructed until 1694. (Interestingly enough, a document he prepared in 1679 speculates on the possibility of constructing a binary calculator, using moving balls to represent binary digits [7].) His machine featured the "stepped reckoner mechanism", which was in effect a set of ten fixed coaxial gear wheels each with a different number of teeth, representing the digits 0 to 9. This mechanism was used in many later machines including those of HAHN (1770), STANHOPE (1775), MÜLLER (1783) and THOMAS (1820). Gradually, with the progress of the Industrial Revolution, manufacturing techniques improved and the needs for convenient methods of calculation became great. However it was not until the mid-nineteenth century that a calculating machine, in fact an improved version of THOMAS' "Arithmometer", achieved commercial success [8].

Thus in 1821, when CHARLES BABBAGE became interested in the possibility of mechanising the computation and printing of mathematical tables, even quite basic calculating machines were still a very uncertain proposition. BABBAGE had been born in 1791, son of a London banker [9]. He was a keen mathematician and while a student at Cambridge University formed with friends the Analytical Society, with the aim of promoting the notation for the differential calculus that LEIBNIZ had invented, in place of that of NEWTON. By 1816 he had been elected a Fellow of the Royal Society, and he was later actively involved in the founding of the British Association for the Advancement of Science and what became the Royal Astronomical Society. Although his major life interest was the development of automatic calculating machines, he also made valuable contributions to an amazing number of subjects — in all he published some eighty papers and books, including works on mathematics, physics, astronomy, geology, theology, economics, statistics and government.

BABBAGE's idea was to build a difference engine, consisting of a set of linked adding mechanisms, capable of automatically generating successive values of algebraic functions by means of the method of finite differences. Such a scheme had been suggested thirty-five years earlier by MÜLLER [10] as a possible development of his circular version of a Leibniz-style calculating machine, but there is no evidence that he ever built such a machine, or that BABBAGE knew of his plans. In 1822 BABBAGE made a small working model of his difference engine capable of handling two orders of difference. This in fact was to be the only calculating machine he ever successfully completed. As it was, this model encouraged him to plan a full scale machine and to seek financial backing from the government.

During the next twelve years, both BABBAGE and the government poured considerable sums of money into the attempt at building the Difference Engine. The eminent machine-tool builder JOSEPH CLEMENT was hired to work on the project, which turned out to be considerably beyond the technological capabilities of the era — indeed it has been claimed that the efforts expended on the Difference Engine were more than justified simply by the improvements that they generated in mechanical engineering equipment and practices. However many disputes arose between BABBAGE and both the government and CLEMENT, and work ceased on the Difference Engine in 1833, with CLEMENT taking advantage of his legal right to possession of the machine-tools that had been built specially for the project. The portion of the Difference Engine that had been completed by 1833 is now in the Science Museum, London [11].

As is described in the next chapter BABBAGE then went on to design his Analytical Engine, but a paper describing his Difference Engine was the inspiration of the successful attempt by GEORGE and EDVARD SCHEUTZ to construct a somewhat more modest machine [12]. The first working model was demonstrated in 1843 and with financial assistance from the Swedish Government the final version was completed ten years later. It was successfully exhibited in Paris and London and was then purchased for an American observatory. A copy of the machine was built for the British Government, and used for several years for the computation and printing of tables used for calculating life insurance premiums. In later years further difference engines were constructed by WIBERG [13], GRANT [14] and HAMANN [15] and others were designed by BOLLÉE and LUDGATE, but never constructed. However such machines never achieved the importance of more conventional calculating machines, and when multi-register accounting machines became available it was found that these could be used essentially as difference engines [16].

During the hundred years between BABBAGE's first plans for an Analytical Engine and the earliest program-controlled digital computers an incredible variety of mechanical calculating machines were developed, and came into widespread use for both technical calculations and commercial book-keeping purposes [17]. However their influence on computer developments would appear to have been largely indirect — indeed, although it is hardly conceivable that BABBAGE was not influenced by contemporary and previous attempts at constructing mechanical calculating devices, his own designs showed considerable ingenuity. In all probability the main importance of mechanical calculating machines was that, together with punched card equipment, they led to the general acceptance of the idea of mechanised digital calculation, and so as the needs for greater speed and accuracy became apparent, helped to pave the way for the development of automatic computers.

Sequence Control Mechanisms

The idea of using a sequence control mechanism so that a machine can perform very complex actions consisting of a sequence of perhaps quite simple basic operations is a very old one indeed. The earliest such mechanism was the rotating pegged cylinder still seen in music boxes today. Such cylinders are believed to date from the fourteenth century, when they were used to control the movements of model figures decorating large church clocks [18]. Later they were used to control pipe organs, and for example in the late sixteenth century DE CAUS used such a mechanism to control both the playing of an organ and several figures [19]. However such cylinders were regarded as an integral part of the machine they were controlling rather than as being the means by which a general purpose machine was set up to do a specific series of actions, although there was the idea of altering individual pegs. The idea of controlling a machine by sequencing information held on some separate medium seems to have arisen first in the silk-weaving industry; it was not until the mid or late nineteenth century that such schemes as interchangeable pegged cylinders and perforated discs and tapes were used in automatic musical instruments [20].

Very little is known about BASILE BOUCHON, who is credited with inventing, in 1725, the idea of using a perforated tape to control the weaving of ornamental patterns [21]. Looms for weaving figured silk, called draw looms, were originally operated by two people, one to control the shuttle which passed the weft thread from side to side of the material being woven, and an assistant to control by means of cords the choice of which warp threads were to be lifted for each passage of the shuttle. BOUCHON's scheme was to control the choice of cords to be pulled by a row of perforations across a tape, and to reduce the task of the weaver's assistant to that of pressing the mechanism over which the tape was hung against a set of needles, which in effect sensed which holes had been punched.

During the next few years the basic scheme was greatly improved by FALCON, a master silk weaver in Lyons, in collaboration with BOUCHON. FALCON extended

BOUCHON's rather limited machine by using several rows of needles so that four hundred or more cords could be controlled, and replaced the perforated tape by a set of strung-together perforated cards. The Falcon draw loom achieved a certain amount of success, and when he died in 1765 about forty were in operation.

The next important development was by VAUCANSON, the celebrated designer of mechanical automata [22] who for example in 1736 had successfully demonstrated an automaton which simulated human lip and finger movements with sufficient accuracy to play a flute. VAUCANSON's contribution to the draw loom was to design in about 1750 the first draw loom to function completely automatically, without the need for even a single operator. However he took the somewhat retrograde step of substituting a perforated cylinder for the effectively unbounded set of perforated cards.

It was left to JACQUARD, assisted by BRETON, to improve VAUCANSON's automatic loom, and also to return to FALCON's idea of using perforated cards, and so in the first decade of the nineteenth century make the first really successful automatic draw loom. Thousands of examples of the Jacquard loom, as it became known, were soon in operation, so that BABBAGE's decision in 1836 to use Jacquard mechanisms as program-control devices for his Analytical Engine was an eminently practical one.

The one other direct influence which the Jacquard loom is claimed to have had on the origins of computers is through the work of HERMAN HOLLERITH, inventor of the first punched card tabulating system. His system, which is described in Chapter 3, was based on electrical sensing of card perforations; it is interesting to note that in Italy in the 1850's BONELLI, BOLMIDA and VICENZIA experimented with electrical versions of the Jacquard mechanism [23]. However the evidence that HOLLERITH was influenced by the Jacquard loom is not very strong, and there is no reason at all to suppose that he knew of this Italian work.

Notes

1. Useful although brief discussions of these aspects of the emergence of computers are given by LILLEY (1945) and SMITH, T. M. (1970).
2. SMITH, T. M. (1970).
3. FLAD (1958), TATON and FLAD (1963), VON FREYTAG LÖRINGHOFF (1957).
4. Many descriptions of the development and workings of PASCAL's machine have been written — a particularly detailed account is given in TATON (1963).
5. See for example BAXANDALL (1929), D'OCAGNE (1905) and JACOB (1911).
6. A description by LEIBNIZ of his machine is included in KORMES (1929).
7. LEIBNIZ (1679).
8. HOYAU (1822), SEBERT (1879).
9. BABBAGE has been the subject of many articles, but as yet one full length published biography, namely MOSELEY (1964). The best account of his work on difference engines is included in COLLIER (1970).
10. KLIPSTEIN (1786).
11. BABBAGE, B. H. (1872).
12. ARCHIBALD (1947 a), ANON (1855).
13. DELAUNAY (1863).
14. GRANT (1871).
15. GALLE (1912).
16. COMRIE (1928, 1946 a).
17. MARTIN, E. (1925) describes well over 200 different calculators, by almost as many different inventors.

18. Goldscheider and Zemanek (1971).
19. Chapuis and Droz (1949).
20. Buchner (1950).
21. Accounts of the development of automatic looms are to be found in, for example, Ballot (1923), Eymard (1863) and Usher (1954).
22. Doyon and Liaigre (1966).
23. Barlow (1878).

Chapter
II
Analytical Engines

Almost as soon as he started work on his Difference Engine in 1822 BABBAGE became dissatisfied with its limitations. In particular he wished to avoid the need to have the highest order of difference constant, in order to be able to use the machine directly for transcendental functions as well as algebraic functions of up to the sixth order. He does not seem to have paid much attention to this problem until 1834, after CLEMENT had withdrawn from the project and work on the Difference Engine had been suspended. However BABBAGE then began to investigate the design of a multiplication mechanism and of means for connecting the accumulator to the highest order difference, so that the latter would not have to remain constant. He referred to this as "the engine eating its own tail", a scheme which WILKES has described as a form of digital differential analyser [1].

During the winter of 1834 and the spring of 1835 his ideas evolved as he considered problems such as division and the need to speed up the carriage (i.e. carry assimilation) mechanism [2]. In the Difference Engine carry assimilation had been sequential, and for lengthy numbers could take much longer than the basic addition. One technique that BABBAGE investigated involved deferring the assimilation of carry digits until the end of a sequence of up to nine additions, by storing the carry digits in a "hoarding carriage". However, he then started to investigate techniques of speeding up a single addition, and developed perhaps his single most ingenious invention, the "anticipating carriage", which performed parallel carry assimilation. The time savings so obtained were at the cost of a considerable amount of complex machinery, and BABBAGE began to see the great advantages from the point of view of economising on equipment of having a single centralised arithmetic mechanism, the "mill", separate from the "figure axes", i.e. columns of discs which acted merely as storage locations rather than accumulators.

BABBAGE's first idea for controlling the sequencing of the various component mechanisms of the engine was to use "barrels", i.e. rotating pegged cylinders of the sort used in musical automata — he had been fascinated by such automata as a child, and possessed a silver dancing figure. His earliest notes on the use of barrels are dated February 1835. In the next two months he developed a scheme for double precision arithmetic and improved methods of multiplication and division, the former being based on the use of a built-in multiplication table. The first public announcement of the new machine, which he later came to call his "Analytical Engine", was made at this time in a letter to M. QUETELET of the Royal Academy of Sciences at Brussels [3]. The letter ends, characteristically:

"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."

By July 1835 he was planning to use a set of subsidiary barrels, one for each different variable, i.e. storage location, with overall control being specified by a large central barrel with changeable pegs or "studs". He continued to work intensively on the machine and, for example, investigated the design of output devices, including an automatic curve drawing apparatus and a printing mechanism. Then at the end of June 1836 he took the major step of adopting a punched card mechanism, of the kind found in Jacquard looms, in place of the rather limited and cumbersome central barrel [4]. The reasons he gave for this decision were as follows [5]:

"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 of the drums, and the Jacquard pasteboards will circulate.
Every formula ever put into the machine will be preserved.
The extent of the formulae is almost unbounded."

No detailed account of the workings of the Analytical Engine was ever published. However there still exists a manuscript written by BABBAGE in December 1837 which gives a fairly full account of his machine. This manuscript, together with others, was given by BABBAGE to his friend H. W. BUXTON, and is now in the Buxton MSS Collection at the Museum of the History of Science, Oxford. The manuscript is, after all these years, somewhat illegible and difficult to follow. Fortunately BUXTON had fair copies made of most of the manuscripts, and incorporated extensive verbatim quotations from the manuscripts in his unpublished biography of BABBAGE. These have been used to facilitate the transcription of the 1837 manuscript which is given in full on pages 17—52 of this book, with the original spelling retained, although slight changes have been made to the punctuation. In several places, as with the original manuscript, it will be seen that blanks appear, where BABBAGE had not got around to inserting numerical estimates concerning the expected performance of his machine.

The overall layout of the machine at the time of preparation of this account was much the same as given in the general plan, published three years later, and which is shown in figure 1 — this is perhaps the same plan that BABBAGE intended to accompany his manuscript. Here the mill is arranged around the set of central wheels, at the end of the rack which serves as the link to the various figure axes constituting the storage registers. Another, unpublished, plan (figure 2) shows the Jacquard mechanism, and one of the subsidiary barrels which performed the sequencing of the set of primitive operations which were called into action by a particular operation card, and which in turn could control whether the Jacquard mechanism was turned on ("turned") or turned back ("backed").

Thus, in the space of perhaps three years from the start of his work on the Analytical Engine in 1834, BABBAGE had arrived at the concept of a general purpose digital computer consisting of a store, arithmetic unit, punched card input and output, and a card-controlled sequencing mechanism that provided iteration and conditional branching. Moreover, although he continued to regard the machine as being principally for the construction of mathematical tables, he had a very clear grasp

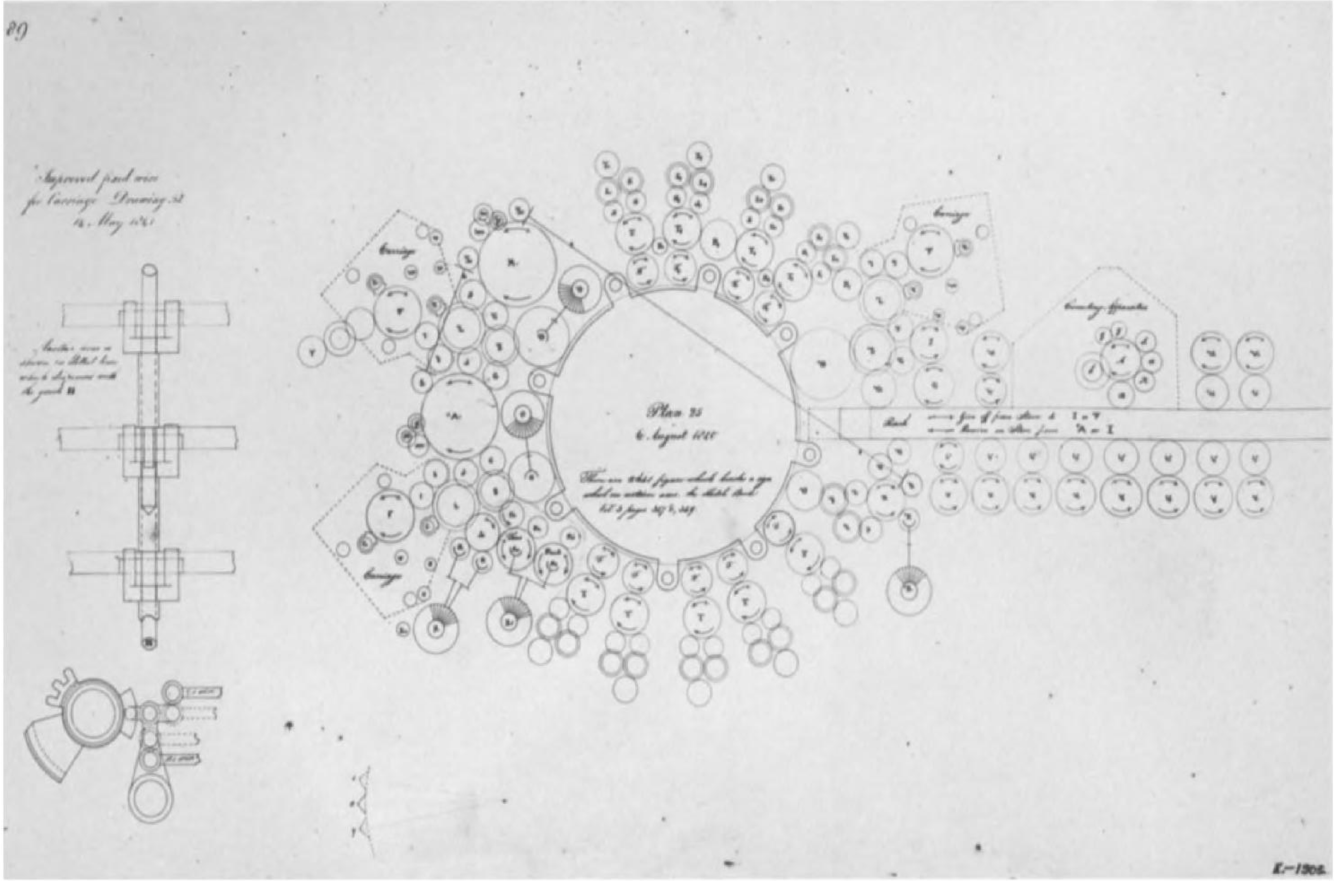
Improved fixed wire
for Carriage Drawing 32
14 May 1841
Plan 25
6 August 1840
Rack
Carriage
Carriage Apparatus

Fig. 1

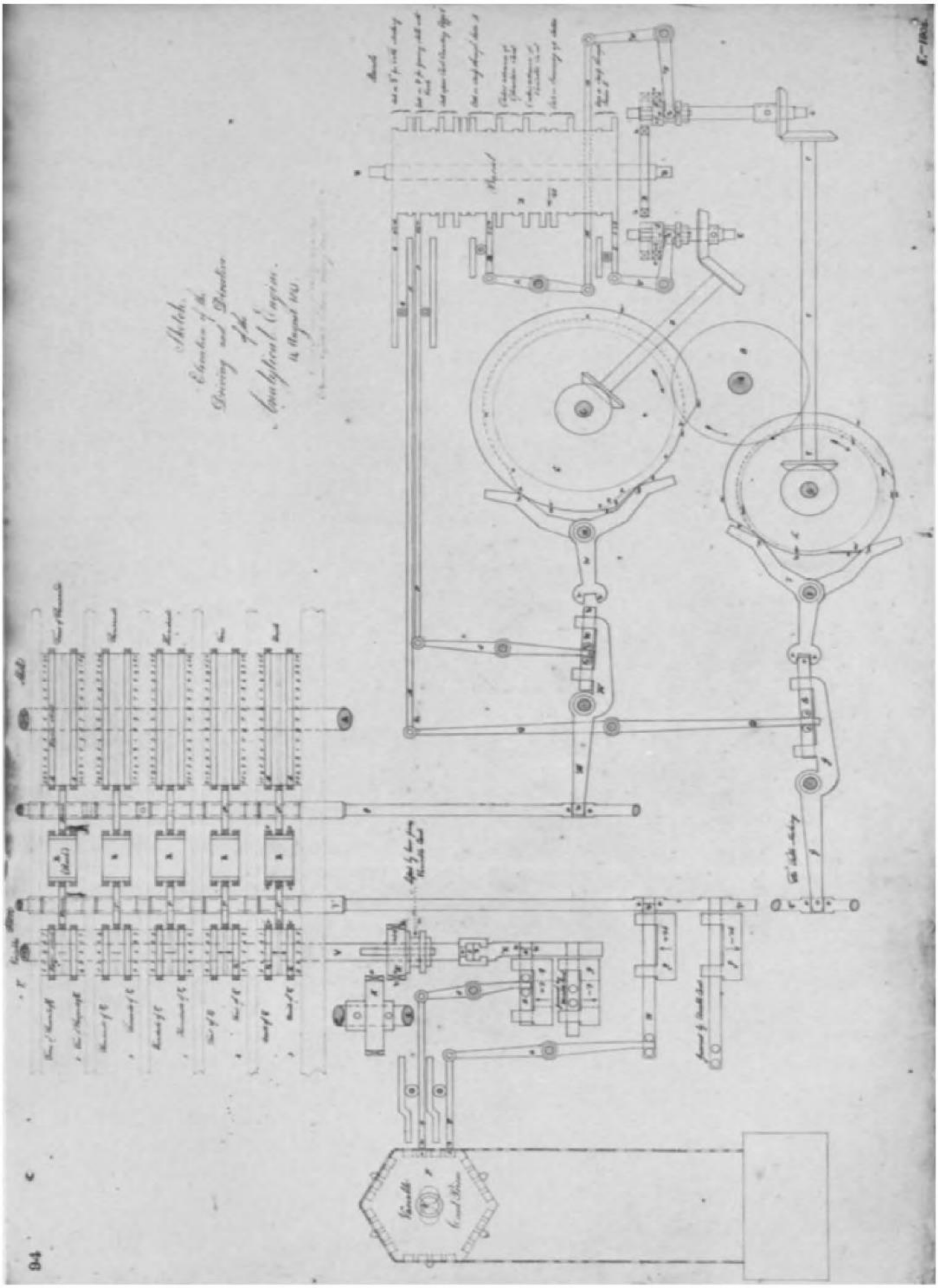
Sketch,
Elevation of the
Driving and Direction
of the
Analytical Engine.
14 August 1841
94

Fig. 2

of the conceptual advances he had made. In particular, in later writings, he laid great stress on the facts that:

(i) by the use of multiple precision arithmetic the limitations of what we would now call the machine's word length could be overcome;

(ii) by punching out intermediate results storage size limitations could be relaxed;

(iii) an unbounded number of operation cards could be used, and the machine could itself determine, based on whether or not "running up" (i.e. overflow) had taken place, the future course of the calculation — "Mechanical means have been provided for backing or advancing the operation cards to any extent. There exist means of expressing the conditions under which these various processes are required to be called into play. It is not even necessary that two courses only should be possible. Any number of courses may be possible at the same time; and the choice of each may depend upon any number of conditions [6]".

It was on these facts that he based his claim that:

"... it appears that the whole of the conditions which enable a *finite* machine to make calculations of *unlimited* extent are fulfilled in the Analytical Engine ... I have converted the infinity of space, which was required by the conditions of the problem, into the infinity of time [7]".

BABBAGE continued to work on the Analytical Engine until 1846, in particular on improved carriage, multiplication and division mechanisms, on its overall layout, and on control sequencing techniques — he eventually dispensed with the "combinatorial cards" of the 1837 paper in favour of the operation cards themselves holding index numbers which could be used to control iteration loops. Detailed discussions of this work have been given by WILKES (1971) and COLLIER (1970). The former study is of particular interest because of WILKES' own role in the development of computers (see Chapter 8); WILKES states that it is "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 ... a world so recognizably like that into which I was plunged 25 years ago."

In 1840 BABBAGE accepted an invitation from the Italian mathematician GIOVANNI PLANA to attend a scientific meeting in Turin. He took much information about his design with him to Turin. The meetings at which he described his machine were attended by a young military engineer, L. F. MENABREA, who at BABBAGE's suggestion drew up an account of the Analytical Engine which was published in 1842. This account was translated into English by AUGUSTA ADA, Countess of LOVELACE, the only legitimate daughter of Lord BYRON. Lady LOVELACE, a gifted young mathematician, had become interested in the machine in 1841, and in consultation with BABBAGE, she added a series of lengthy notes to the translation, including what was in essence a quite sophisticated program to compute Bernoulli numbers, which had initially been drawn up by BABBAGE. The annotated translation, published in 1843, was the single most important published account of the Analytical Engine, and is particularly valuable for its commentary on the capabilities and limitations of the engine, even though it gives comparatively few details of its mechanical design. Especially now, with our knowledge of modern computers, this account, which has been reprinted several times and quoted from extensively, makes fascinating reading and shows clearly how far ahead of its time was the thinking that went into the Analytical Engine.

It would appear that during the first phase of development of the Analytical Engine, BABBAGE had no immediate intention of trying to construct one. In 1846, thinking perhaps that the change of government presaged a more favourable official attitude to his endeavours, he returned to the subject of difference engines. He did little further work on the Analytical Engine until 1857, when he started to investigate the possibility of actually constructing one, perhaps influenced by the successful construction of the Scheutz difference engine, and by the improved state of mechanical engineering. From then on, until his death in 1871, he continued to work intermittently on the Analytical Engine, investigating and re-investigating various design problems, and constructing various trial pieces of mechanism. Interestingly enough there is evidence [8] that during this period he learnt of the work in Italy on an electrical version of the Jacquard loom, but apparently he never considered anything other than a mechanical engine, driven like a clock by falling weights, which would be periodically raised by manual or steam power.

BABBAGE died a disappointed man — his calculating machines had been his main passion in life, though as mentioned earlier he had worked on many other subjects and had some eighty published books and papers to his credit. His lack of success in constructing a useful calculating machine was due in part to his own perfectionism, and in part to the inadequacy of the technology of his day and to the fact that comparatively few of his contemporaries shared his beliefs in the need for such machines. However this does not detract from the incredible intellectual attainment that is constituted by his plans for the Analytical Engine and his understanding of its theoretical capabilities. Indeed we will see that the earliest program-controlled computers, namely those of ZUSE and AIKEN in the early 1940's, were conceptually hardly a match for BABBAGE's engine.

After BABBAGE's death in 1871 his son Major General HENRY BABBAGE continued to work on the Analytical Engine, and completed the assembly of part of the Mill and a printing apparatus with which he successfully demonstrated the working of the anticipating carriage [9]. In 1878 a Committee of the British Association for the Advancement of Science reviewed the Analytical Engine in order to determine whether it should receive official support — their report is reprinted on pages 53—63. HENRY BABBAGE later built a second mill and printing apparatus which he demonstrated in 1910 at a meeting of the Royal Astronomical Society with a fair measure of success — see the account by HENRY BABBAGE reprinted on pages 65—69 [10]. Thus the saga of BABBAGE's Analytical Engine came to an end, although its fame lingered on and inspired several other people to attempt what BABBAGE had failed to achieve.

The first of these was PERCY LUDGATE, a Dublin accountant, who in 1903 at the age of twenty started to design an "Analytical Machine". The arithmetic unit and the store were so different from BABBAGE's designs that there is little reason to doubt LUDGATE's claim that his early work was done in ignorance of BABBAGE's efforts. In fact his design for the arithmetic unit, whose multiplier used a form of logarithms in order to calculate two-digit partial products, is quite unlike anything known to have gone before. It is not known at what stage LUDGATE learnt about the "mathematical principles" of BABBAGE's machines, but it seems likely that these inspired LUDGATE to investigate the provision of a sequence-control mechanism. Here he made an advance over the rather awkward system that BABBAGE had planned, which involved separate sets of operation and variable cards. Instead his machine was controlled by a perforated tape, each row of which represented an instruction consisting of an operation code and four address fields. Control transfers simply involved moving the tape the appropriate number of rows forwards or backwards.

Very little is known about LUDGATE's life [11]. He apparently worked alone on his Analytical Machine in his spare time. There is no evidence that he ever tried to construct the machine, but instead abandoned work on it in favour of a much simpler machine more in the nature of a difference engine, which again probably never got past the design stage [12]. His work during the first world war provided another point of similarity to BABBAGE's career because he was involved in the vast task of planning and organizing the provision of supplies for the cavalry. This was essentially a problem in operational research, a subject that in part originated with BABBAGE's influential book "On the Economy of Manufactures and Machinery". LUDGATE died in 1922, and even if at this time his plans for the Analytical Machine still existed, there is now no trace of them; our knowledge of the machine depends on the one little-known description of it that he published, which is reprinted on pages 71—85.

The second person who is known to have followed in the footsteps of BABBAGE and to have worked on the problems of designing an analytical engine was LEONARDO TORRES Y QUEVEDO. TORRES was born in the province of Santander in Spain in 1852. Although qualified as a civil engineer he devoted his career to scientific research, and in particular to the design and construction of an astonishing variety of calculating devices and automata. He gained great renown, particularly in France and in Spain, where he became President of the Academy of Sciences of Madrid, and where following his death in 1936 an institute for scientific research was named after him [13].

TORRES first worked on analogue calculating devices, including equation solvers and integrators. In the early 1900's he built various radio-controlled devices, including a torpedo and a boat which, according to the number of pulses it received, could select between various rudder positions and speeds, and cause a flag to be run up and down a mast. The boat was successfully demonstrated in 1906 "in the port of Bilbao in the presence of the King and a considerable crowd". In 1911 he made and successfully demonstrated the first of two chess-playing automata for the end game of king and rook against king. The machine was fully automatic, with electrical sensing of the positions of the pieces on the board and a mechanical arm to move its own pieces. (The second machine was built in 1922, and used magnets underneath the board to move the pieces.) In all this work, he was deliberately exploiting the new facilities that electro-mechanical techniques offered, and challenging accepted ideas as to the limitations of machines. His attitude is well summarised by the following quotation from an American article giving a detailed description of the workings of the first chess automaton [14]:

"There is no claim that [the chess player] will think or accomplish things where thought is necessary, but its inventor claims that the limits within which thought is really necessary need to be better defined, and that the automaton can do many things that are popularly classed with thought. It will do certain things which depend upon certain conditions, and these according to arbitrary rules selected in advance."

His most important paper from our point of view is his "Essais sur l'Automatique", a translation of which is given on pages 87—105. The term "automatique" was one of his own invention, which could well be translated into the then-unknown "automation". However, to avoid possible false connotations it has instead been merely transliterated into "automatics". This paper, written in 1914, was published in both Spain and France, and makes clear his knowledge of, and admiration for, BABBAGE's Analytical Engine. In the paper, in order to prove his contentions regarding the practicality of using electromechanical techniques to build a "universal automaton", i.e. one capable of exercising judgement, TORRES provides a schematic design for a digital calculating machine. This machine, though special purpose, is very much a program-controlled device, and incorporates a fully worked-out scheme for conditional branching.

TORRES clearly never intended to construct a machine to this design, but six years later he built a calculating machine which is described in detail in the translation of the paper appearing on pages 107—118. The machine, which was successfully demonstrated in France in 1920, was built primarily to demonstrate that an electromechanical analytical engine was completely feasible. He in fact never did build an analytical engine, though he designed, and in many cases built, various other devices to illustrate his concept of "automatics", including two more calculating machines, an automatic weighing machine, and a machine for playing a game somewhat like the game of Nim. However there seems little reason to doubt that, should the need have been sufficiently pressing, TORRES would indeed have built a complete analytical engine. As we will see in later chapters, it was not until the 1939—1945 war that the desirability of large scale fully-automatic calculating machines became so clear that the necessary environment was created for BABBAGE's concept to become a reality.

Before this occurred there is known to have been at least one further effort at designing an analytical engine. This was by a Frenchman, LOUIS COUFFIGNAL, who was motivated mainly by a desire to reduce the incidence of errors in numerical computations. A section of a monograph he wrote in 1933 is reprinted in the next chapter, because it is mainly concerned with punched card equipment, but this makes clear the extent to which he was inspired by BABBAGE's plans. In this chapter we include a translation of a brief extract from his Ph. D. Thesis, written in 1938, describing a binary electromechanical program-controlled calculator. (The translation appears on pages 119—123 — for convenience the sections and figures have been renumbered.) This is one of two such designs in the thesis, the other being for a decimal machine. However the main theme of the thesis is a detailed scheme of classification for the various existing types of calculating machine, which extends the earlier work along these lines by D'OCAGNE.

COUFFIGNAL apparently had every intention of building this machine in association with the Logabax company, but presumably because of the war never did so. However, after the war he was in charge of an electronic computer project for the Institut Blaise Pascal, the design study and construction of the machine being in the hands of the Logabax company.

With COUFFIGNAL's pre-war plans, the line of direct succession to BABBAGE's Analytical Engine seems to have come to an end. Most of the wartime computer projects were apparently carried out in ignorance of the extent to which many of the problems that had to be dealt with had been considered and often solved by BABBAGE over one hundred years earlier. However in some cases there is clear evidence that knowledge of BABBAGE's work was an influence on the wartime pioneers, in particular HOWARD AIKEN (see Chapter 5) and WILLIAM PHILLIPS (see Chapter 7), and various other influential people, including VANNEVAR BUSH and L. J. COMRIE, were also well aware of his dream.

Notes

1. WILKES (1971).
2. The description of the evolution of the Analytical Engine is derived mainly from the detailed analysis by COLLIER (1970) of information in the Buxton Collection of manuscripts at Oxford, and BABBAGE's sketchbooks and drawings at the Science Museum.
3. BABBAGE, C. (1835).
4. It is interesting to note that as a boy CLEMENT had learnt to use a hand loom, and later had designed a power loom (SMILES (1908)).
5. Quoted by WILKES (1971).
6. BABBAGE, C. (1864).
7. BABBAGE, C. (1864).
8. Letter to BABBAGE from WILLIAM GRAVATT, dated 3 Feb. 1860, quoted by COLLIER (1970).
9. BABBAGE, H. P. (1888).
10. Both of the machines put together by HENRY BABBAGE are now in the Science Museum.
11. What little is known about LUDGATE is documented in RANDELL (1971).
12. LUDGATE (1914).
13. The main accounts of the life and work of TORRES Y QUEVEDO are D'OCAGNE (1937) and TORRES-QUEVEDO (1951 a, 1951 b).
14. ANON (1915).

[26. Dec. 1837]

On the Mathematical Powers of the Calculating Engine

2.1.

By CHARLES BABBAGE

The object of the present volume is to show the degree of assistance which mathematical science is capable of receiving from mechanism. I may possibly in a separate work describe minutely the mechanism I have contrived for that purpose. For the complete understanding of the following pages it will be unnecessary to present to the reader more than a very general outline of the structure of the engine and if he feel indisposed to examine even that, he may pass it over and taking certain mechanical data for granted at once proceed to the mathematical investigation in which he will find that they are all proved to depend on those mechanical data.

The calculating part of the engine may be divided into two portions
1st The *Mill* in which all operations are performed
2nd The *Store* in which all the numbers are originally placed and to which the numbers computed by the engine are returned.

The plate represents a plan of the engine — those circles placed round the great central wheel constitute the Mill whilst that portion which adjoins the longitudinal part or rack represents the Store.

Of the Mill

Two Axes with figure wheels, I the *Ingress Axis* and "A the *Egress Axis* connect the *Mill* with the *Store.*

The Mill itself consists of: —

1. Three Figure Axes
2. Three Carriage Axes
3. Ten Table Figure Axes
4. Digit Counting Apparatus
5. Selecting Apparatus
6. Barrels
7. Reducing Apparatus for Barrels
8. Operation Cards
9. Repeating Apparatus
10. Combinatorial Counting Apparatus

1. *Of the Figure Axes*

The Figure Axes A and 'A are connected with each other without the intervention of the central wheels so that a number on the figure wheels of one axis may be transferred to those of the other.

These figure wheels are considerably larger than any others in order to allow of sufficient space on their circumference for placing the pinions by which communications are made with other parts of the mill.

By means of some of these pinions a process called *Stepping down* and another called *Stepping up* may be performed. It consists in shifting each digit of a number one cage lower or one cage higher, which processes are equivalent to the arithmetical operations of dividing or multiplying the number by ten.

Other pinions are fixed on *register axes* R and R_1 and convey the two highest figures of the dividend to the *Selecting* apparatus. The third figure axis "A is placed near the Store and constitutes the egress axis. It is adjacent to the digit counting apparatus with which it communicates.

2. *Carriage Axes*

These Axes F, 'F, "F with their peculiar apparatus are employed to execute the carriage of the tens when numbers are added to or subtracted from each other. The carriages F and 'F can be both connected with the Figure Axis A or one of them with the Figure Axis A and the other with 'A or they may by means of the central wheels be connected with any other part of the Mill. The third carriage "F is connected both with the Mill and the Store and may be used with either.

Whenever the number subtracted is greater than that from which it is taken the resulting carriages would if effected, and if the mechanism admitted, produce a carriage in the forty first cage. This fact is taken advantage of for many purposes — it is one of very great importance and when it happens a *Running up* is said to occur. Connected with this part is a lever on which the *Running up* warning acts and this lever governs many parts of the engine according as the circumstances demand.

3. *Table Figure Axes*

These Axes are ten in number, nine of them contain the table of the nine multiples of one factor in Multiplication and of the Divisor in Division. The tenth contains the complement of the Divisor in the latter operation. They are all connected with the central wheels and the number on each figure wheel can be *stepped up* or *down* upon the other figure wheel of the same cage. The figure which at each stepping goes off from the bottom wheel is transferred to the top wheel.

4. *Of the Digit Counting Apparatus*

This is a mechanism by which the digits of any number brought into the mill may be counted and certain calculations made as to the position of the decimal point in the result of multiplication and division. It is also used to limit the number of figures employed when the engine is making successive approximations either to the roots of equations or to the values of certain functions. It consists of three distinct systems nearly similar to each other.

5. *Of the Selecting Apparatus*

When a table of the nine multiples of a multiplicand has been made it becomes necessary in order to effect multiplication to select successively those multiples indicated by the successive digits of the multiplier. This mechanically is not difficult. But when in the process of division it becomes requisite to select that multiple which is next less than the dividend from which it is to be subtracted the mechanical difficulty is of quite a different order and hitherto nothing but the most refined artifices have been found for accomplishing it. This refinement relates however entirely to the *nature* of those contrivances not to the certainty of their action nor to any delicacy of workmanship.

The apparatus consists of a portion of the carrying apparatus for three figure wheels which by the addition of another contrivance renders them available for the purpose of making the selection. This apparatus is placed immediately below the Table Axes.

[6] *Of the Barrels*

The barrels are upright cylinders divided into about seventy rings the circumference of each ring being divided into about eighty parts. A stud may be fixed on any one or more of these portions of each ring. Thus each barrel presents about eighty vertical columns every one of which contains a different combination of fixed studs.

These barrels have two movements:

1st: They can advance horizontally by a parallel motion of their axis

2nd: They can turn in either direction and to any extent on their axis.

When the barrels advance horizontally these studs act on levers which cause various movements in the mill, the stud belonging to each ring giving a different order.

Amongst these movements or rather these orders for movements the following may be more particularly noticed. The advance of a barrel may order: —

a) A number with its sign to be received into the mill from the ingress axis.

b) A number with its sign to be given off from the mill. This number may thus be either altogether obliterated from the mill or it may at the same time be received on

Various parts may be added to the store according to the purposes required. Some of them might perhaps with more convenience constitute distinct machines.

The store then may contain: —

a) Figure Axes
b) Computing Apparatus
c) Number Cards
d) Card punching Apparatus
e) Printing Apparatus
f) Copper Punching App.^{s}
g) Curve Drawing App.^{s}
h) Variable Cards.

The Figure Axes and the Variable Cards alone are absolutely necessary for the mathematical enquiries in the present work and for the sake of simplicity the others will be only occasionally referred to.

1. *Of the Figure Axes*

A number of axes each having forty figure wheels placed in different cages one above another are connected with the rack of the Store.

These figure wheels are each numbered from 0 to 9; they may be turned by hand so that any digit may stand opposite a fixed index. Thus any number of not more than forty places of figures may be put upon the figure wheels of each axis.

Above the fortieth cage is another cage containing a wheel similar to a figure wheel and also having its circumference divided into ten parts. These parts have the signs (+) plus and (−1) minus alternately engraved upon them. Above this wheel is a fixed character to distinguish each particular axis or rather the variable number which may be found upon its wheels. These fixed marks are v_1, v_2, . . . v_{32}, . . . as far as the number of quantities which can be contained in the store.

Below the lowest or units figure wheel a small square frame appears in which may be inserted a card to be changed according to the nature of the calculation directed. On this card is written that particular variable or constant of the formula to be computed whose numerical coefficient and sign are expressed on the wheels above it.

The annexed representation will perhaps convey a clearer idea of this part of the engine.

The first line of quantities v_1 v_2, . . . are never altered; they merely indicate the particular sets of figure wheels to which they are attached.

The next line contains the *signs* of the quantities which are themselves expressed by writing them upon pieces of card and placing them in the squares at the bottom.

The intermediate forty cages contain the numerical coefficients.

The first variable or v_1 is in the present figure equal to zero and previously to the setting of the engine to any problem, all the other variables v_2, v_3, v_4, . . . have the same symbols beneath them.

The second variable v_2 has beneath it the negative sign, the number 1758 and the algebraic quantity a.

	Variables of the Engine	v_1	v_2	v_3	v_4	v_5	v_6
Signs	Cage 41	+	−	+	−	+	+
Numerical Coefficients	Cage 40	0	0	0	0	0	0
	Cage 39	0	0	0	0	0	0
	. . . . . .	. . .	. . .	. . .	. . .	. . .	. . .
	. . . . . .	. . .	. . .	. . .	. . .	. . .	. . .
	Cage 5 Tens of Thousands	0	0	0	2	0	0
	Cage 4 Thousands	0	1	4	3	0	0
	Cage 3 Hundreds	0	7	9	4	0	2
	Cage 2 Tens	0	5	7	1	3	4
	Cage 1 Units	0	8	1	0	6	7
Variables of the Question			a	x	x^3	$\sin\theta$	$\sqrt{a^2+x^2}$

The symbols placed on the engine are in the annexed figure

$v_1 = 0$ $\qquad$ $v_4 = -23410x^3$

$v_2 = -1758a$ $\qquad$ $v_5 = +36\sin\theta$

$v_3 = +4971x$ $\qquad$ $v_6 = +247\sqrt{a^2 + x^2}$

In this manner any function however complicated it may be if it is considered as a whole may be placed in the store with its proper sign and its numerical coefficient; the function itself being merely written on a card and placed in the square below its coefficient. The number of variables which can be contained within the store will depend on the length of the rack and number of figure axes which can be placed round it and although a large number of variables might with perfect safety be employed yet there is obviously a practical limit arising from the weight of the rack to be moved.

One hundred variables would not give an inconveniently large rack but still the calculations of such an engine would be limited. This limitation can be entirely removed by another set of cards called Number Cards which will presently be described.

If any of the coefficients contain decimals or if the result is required with any number of decimals then all the coefficients must be considered as having the same number of decimals. If an imaginary line is drawn between any two cages, the third and fourth for example, then all below it may be considered as decimals. In order to convey to the Engine this information there exists a wheel with the numbers from 1 to 40 engraved on its edge; this wheel being set at any number the Engine will treat all the numbers put into the Store as having that number of decimals.

2. *Of the Computing Apparatus*

One of the Figure Axes K has its figure wheel connected with the rack differently from the others. It is also connected with the Carrying Axis "F belonging to the mill from which however it may at times be disconnected.

The object of this is to enable the figure wheel on the rack to make certain simple calculations without the necessity of sending the numbers into the mill. During the process of one of the great operations in the Mill a series of numbers may be computed in the store by the method of differences and thus a considerable saving of time effected.

3. *Of the Number Cards*

The Number Cards have been introduced for the purpose of rendering the calculations absolutely unlimited by the too great number of variables and constants necessary for the solution of any problem.

The number cards are pierced with certain holes and stand opposite levers connected with a set of figure wheels placed on the Number Axis which can be made at intervals to communicate with the rack. When these Number Cards are advanced they push in those levers opposite to which there are no holes on the cards and thus transfer that number together with its sign which the holes on the card represent to the figure wheels of the axis opposite to which the Cards are placed. The number and its sign thus put upon these figure wheels may be immediately transferred to another part of the Store and the string of number cards being turned the next card conveys its number to the Store in the same way.

These number cards are for some purposes more convenient than figure wheels because the numbers upon a figure card are not obliterated by the act of giving them off. For by turning the string of figure cards back to any given one the number upon that card can be replaced in the Store as frequently as may be required and at any periods of time which the calculation may demand. On the other hand the numbers placed upon figure wheels are always obliterated in the act of giving them off. If it is necessary to retain on the Store any number which is to be given off to the Mill then it also must be given off through the rack to another store axis on whose figure wheels it must remain untill at a second operation it is reconveyed by rack back to its original place.

4. *Card Punching Apparatus*

One mode of rendering permanent the results of any calculations made by the engine will obviously be by making it punch on cards certain holes similar to those just described as existing on the Number Cards. This plan will also enable us to use any intermediate computation which may be necessary in advancing towards the final results, for the cards so made may from time to time be removed from the punching apparatus and attached to the Number Cards. Other advantages will be observed when the subject of mathematical tables comes under consideration.

5. *Printing Apparatus*

It is desireable even when many copies of a calculation made by the engine are not wanted that the results should be themselves printed by the machine in order to ensure the absence of error from copying its answers.

A set of thin circular rings having metal types of the digits fixed at equal distances on their edges and themselves governed by the calculating wheels on which the result is placed are to be pressed down at intervals on a sheet of paper covered by another sheet of carbonised paper. This paper is fixed in a platform having proper motions for placing the printed results in right order.

Thus a single and correct copy may be produced although from the nature of the process the execution of the printing would not be of the highest order.

If however many printed copies are required then it is intended that the type so arranged shall be made to impress their characters on a soft substance from which mould a stereotype plate may be cast.

6. *Copper Plate Punching App.*^{s}

If it should be deemed necessary to print tables or calculations upon copper-plate an apparatus has been contrived for that purpose. This process is necessarily slower in its operation than the former modes of rendering the calculated results permanent. It has however the advantage of possessing greater clearness; although the additional cost of taking off impression may in some instances be objectionable.

Since however the invention of the number cards these modes of printing or engraving have ceased to become essential parts of a Calculating Engine. The absolute certainty of every printed result can now be obtained although the printing mechanism be totally detached from the calculating portion of the Engine, an improvement which it was impossible to make untill that point of the enquiry was attained.

The cards on which the results are punched may themselves be placed in a distinct machine and from the holes formed in them the new machine may either engrave or print them as it may have been prepared to operate.

7. *Curve Drawing Apparatus*

The discovery of laws from the examination of a multitude of tabulated and reduced observations is greatly assisted by the representation of such tables in the form of curves.

As one of the employments of a calculating engine would be to reduce collections of facts by some common formula I thought that at the time it impressed the computed results it would be desireable that it should mark the point of a corresponding curve upon paper or copper if preferred. The three or four first figures of the table will be expressed by the curve. The contrivances for this purpose are not difficult and their employment does not lengthen the time of the calculation.

8. *Variable Cards*

The Variable Cards are appointed for the government of the various parts which constitute the Store. Like all the other cards they act by pushing forward certain levers placed in front of them. These levers cause the motions of the several parts of the Store which have been described.

It is necessary in the present work to consider only — the Figure Axes — the Number Cards — and the card punching App.^{s}, Variable Cards and Combinatorial Operation Cards.

With respect to these the principle functions of the Variable Cards will be to direct: —

a) A Number and its sign to be given off from any Store Axis to the ingress Axis.
b) A number and its sign to be received upon any Store Axis.
c) Any number and its sign to be given off from the Number Cards to the wheels on the Number Axis.
d) Any number and its sign to be given off to the Card Punching Apparatus and a corresponding Card to be punched.

The number of levers necessary for these purposes is not so large as might at first appear, consequently the Cards need not approach an inconvenient magnitude. For example fourteen levers and their equivalent fourteen holes will be all that is required in the third of the above divisions for eight thousand variables.

If the other appendages to the Store which have been already described should be thought necessary a small number of additional levers must be added.

The time necessary for the mere addition and leaving a notice that the first figure in the right has passed a ten, (which is indicated by putting the unity below the tens figure), must be at least equal to that which is required for the figure wheel to pass over nine divisions. Now the time for adding the first ten which is carried and giving notice of the second will be equal to one division and so on, so that at the end of the sixth carriage a time equal to fifteen divisions will have been passed over and it is to be observed that another division must be allowed because the machine cannot know that there is not another carriage due to the seventh figure.

Thus in an engine having forty figures we should have for every addition and its carriage

for addition	9
for 39 possible carriages	39
	48

So that in fact the time consumed in making the carriage of the tens would be more than four times as much as that required for addition. Modes have been contrived for shortening this time but it is evident there is a limit beyond which it cannot be reduced.

Carriage may postpone its operations: When many additions are to be made to the same quantity, as in multiplication, time might be saved by reserving the notices of Carriage and executing them altogether.

Carriage may anticipate its operations: If the mechanism which carries could be made to forsee[1] that its own carriage of a ten to the digit above when that digit happens to be a nine would at the next step give notice of a new carriage then a contrivance might be made by which, acting on that knowledge, it should effect both carriages at once. Thus, after the addition of the numbers below

Time of Add.$^{\text{n}}$	123456
	346601
Time of 1 Carr.	469057
	1
Time of 2 Carr.	460057
	1
	470057

If at the time of the first carriage the engine knew the next number to which it [was] about to carry was a nine and that consequently it would *afterwards* become necessary to give notice of and to carry another ten then it might be taught to execute both these carriages at the same time and consequently to anticipate the time of the second carriage.

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[1] In substituting mechanism for the performance of operations hitherto executed by intellectual labor it is continually necessary to speak of contrivances by which certain alterations in parts of the machine enable it to execute or refrain from executing particular functions. The analogy between these acts and the operations of mind almost forced upon me the figurative employment of the same terms. They were found at once convenient and expressive and I prefer continuing their use rather than substituting lengthened circumlocutions.

For instance, the expression "the engine *knows*, etc." means that one out of many possible results of its calculations has happened and that a certain change in its arrangement has taken place by which it is compelled to carry on the next computation in a certain appointed way.

This object is of such importance that it is worthy of any labor to obtain a plan at once simple and effective. I have contrived several; that which is adopted in the present engine is perfectly secure and considering the very complicated nature of the conditions it is not very deficient in simplicity. This extreme complication of the conditions will perhaps be more felt by considering the following cases

```
Time of Add.ⁿ        006012345678
                     101987655 22
                     ------------
                     007999990690
Time of Carr.               1  1
                     ------------
                     008000000700

Time of Adding       000436578006412897643805 2
                     0005634238990771023562 48
                     ------------------------
                     000999991895489999990090
Time of Carr.               1  1        1  1
                     ------------------------
                     001000001905490000000100
```

The complexity arises from the circumstance that the result of any carriage *may* effect the value of *every* figure on its left hand and that the effect of *any* carriage may terminate at any digit and a *new* carriage may commence its effect at the succeeding one; and this like its predecessor may or may not be the precursor of many others.

[2.] *Of the Algebraic Signs as Used in Addition*

It has been already stated that above every set of forty figure wheels there is in the forty first cage a sign wheel and also that this sign wheel is divided like the figure wheels into a number of parts which is equal to some multiple of ten, the sign minus being engraved on the odd, the sign plus on the even divisions.

Now when these wheels all stand at zero the sign wheel being also zero will present the positive sign.

When a positive number is added its sign being fixed on some even number the sign wheel of the ingress axis will be advanced by an even number of digits and must consequently present some other even number on which will appear the sign *plus.*

The ingress wheels of the Mill which receive any number receive also its sign but as the number on the ingress wheels was zero and the sign plus the addition merely causes the ingress wheels to stand at the number entering and the sign to remain as it was before, namely at *plus.* For the 41st wheel stood at + or at an even number and the addition of + or any other even number will produce an even number on this wheel and consequently it will still present the sign plus. If on the other hand the number entering has the negative sign then its sign wheel stands at an odd division and as an odd number added to an even one produces an odd number the sign of the number in the ingress wheels will be negative.

the time really required is six turns of the handle. If another quantity (± R) is to be added or subtracted it will require another turn and generally if n quantities with their accidental signs are to be added and substracted the time required for the operations will be

n + 4 turns of the first mover.

The time which the edge of the figure wheel occupies to pass from one figure to the next figure is considered as the unit of time and the space between two adjacent figures is the unit of space. The cases in which that velocity is exceeded are very rare in any part of the machine and only occur when the moving part is carried on to a fixed stop. Wishing to under rather than overrate the speed of its calculations I have assumed that the velocity of the circumference of the figure wheel when moving will be ten feet or one hundred and twenty inches per minute. A single turn of the first mover will according to circumstances be performed either in fifteen or in twenty of such units. In the process of addition cycles of twenty units only are employed and as each unit requires .15708 seconds the addition of two numbers only will require seconds and the addition of n quantities will cost 21.99 or nearly 22 seconds.

[5.] *Multiplication*

The process of multiplication is thus performed by the Engine:

The two factors P and Q with their respective accidental signs being placed on the two sets of figure wheels No. 1 and No. 2 of the Ingress axis an operation card is turned. This directs the barrels through the reducing apparatus to move circularly to the vertical which commences multiplication.

At the next turn the barrels advance and order the reception of one of the factors Q. They also direct themselves to move on their axes to the second vertical belonging to Multiplication.

At the third turn the barrels advance and order the reception of the other factor P from the second set of Ingress wheels. At this turn the factor P is subtracted from the factor Q which had at the preceeding turn been placed upon the figure wheels of ′F. The result of this subtraction determines which of the two factors is largest and consequently which factor is to be tabulated.

Much time is saved by this decision for supposing one factor to contain only four places of figures and the other to contain thirty five figures. Then if a table of the first nine multiples of the first factor were made its multiplication by the other factor would require thirty five additions whilst if the larger factor had been tabulated only four additions would have been necessary. The mechanical mode by which this knowledge is conveyed to the barrels is thus. The barrels after ordering the subtraction of P from Q in the axis ′F direct themselves to move on to another vertical; if P is less than Q no *Running up* takes place and the order thus given by the barrels is obeyed; but if P is larger than Q then a *Running up* takes place and the order given by the barrels to move to a certain vertical is enlarged and they are directed by the Running up lever to move on to a different vertical. This new vertical directs the

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Subject Index

This subject index, compiled by Mrs. J. Horning, covers the text of all the chapters of the book, although the technical descriptions of machines that are given in the reprinted papers are not indexed in great detail. The bibliography is not covered, but references to the terms listed in the index to the bibliography are included in this subject index. The page numbers of the reprinted papers are given in bold face under the names of their authors.