This vast machine displayed at one and the same time a perpetual calendar marking the year, the month, the week, the hours and minutes, and an ecclesiastical calendar which gave the feast days, each day’s office, the positions, oppositions and conjunctions of the stars, the phases of the Moon, the motions of the Sun, the Mystery of the Resurrection, Death, St Hugh, St Odilon, the Feast of the Blessed Sacrament, the Passion, the Blessed Virgin. Each hour was announced by a cock which flapped its wings and crowed twice. Simultaneously an angel opened a door and greeted the Blessed Virgin, the Holy Spirit descended in the form of a dove, the Eternal Father blessed them, and all the figures retired within the clock to the accompaniment of a harmonious peal of bells and bizarre manoeuvres of fantastic animals who moved their eyes and flicked their tongues.

THE FIRST AUTOMATICALLY-SEQUENCEDDIGITAL CALCULATORS

Several centuries were to elapse, however, before the basic concepts of sequential automata were applied to artificial numerical calculation as such. In fact the first digital calculators with an automatic capability of effecting chained sequences of operations following a programme set up in advance in a control mechanism were the difference machines, so called because they relied on the mathematical method known as that of "finite differences"; these, starting from a given value, allowed the calculation of values of a polynomial of the degree n to be replaced by a series of n successive additions.61

These calculators appeared at the beginning of the nineteenth century and were conceived to answer the need, long felt by astronomers and navigators, to establish reliable numerical tables. They comprised a certain number, say n, of registers which could store numbers and a mechanism allowing it to execute this type of chained additions, and they could automatically produce the succeeding values of polynomial expressions of

61 This application of the method of finite differences relies on the fact that, for a polynomial in x of degree n, evaluated for successive integer values of x, the differences between successive values of the polynomial are values of a polynomial of degree n-1, the differences of these are the values of a polynomial of degree n — 2,and so on, the differences of order n being constant.

For instance, therefore, the polynomial x sup 2 +x + 1, as x takes successively the values 1, 2, 3, 4, 5, ... ,
itself assumes the values 1, 3, 7, 13, 21, 31, ... 'The differences between these are 2, 4, 6, 8, 10, ... and the differences between these last are 2, 2, 2, 2, ... Therefore if we are given that a polynomial has constant second-order differences all equal to 2, that its initial value is 1, and that the initial value in the series of first differences is 2, we can proceed as follows, using addition only. The first difference is 2; add this to the 1 and get 3. The (constant) second difference is 2; add this to the first difference and get 4; add this to the 3 and get 7. The second difference is again 2; add this to the first difference (4) and get 6; add this to the 7 and get13. Add the second difference (2) to the first difference (6) and get 8; add this to the 13 and get21.Add the second difference (2) to the first difference (8) and get 10; add this to the 21 and get 31. And soon. [Transl.]

degree less than or equal ton, within the limits of their physical capacities,of course.

The German military engineer Johann H. Muller first conceived the idea for such machines in 1786. As they did not answer to any clearly recognisable social need, this invention was never more than a gleam in the eye, and thus sank into oblivion.

THE FIRST DIFFERENCE MACHINES

But less than thirty years later the idea resurfaced and germinated in the highly fertile mind of a great inventor who was to commit himself to its realisation. At a time when even the most elementary mechanical calculators were rare, the English mathematician Charles Babbage (1792—1871) demonstrated in 1822 that this concept was perfectly feasible, then devoted the next eleven years to the construction of a machine of this type. And thus it was, according to the report made by Merrifield to the British Association for the Advancement of Science, that "Babbage is intent uponthe realisation of a mechanical marvel", an idea so ingenious and fertile that it could not but strike the imaginations of all who were called upon to pronounce on it. However, in spite of financial support from the British government and of considerable sums invested from the personal assets ofthe inventor, this project was never really carried through to completion.

There are at least two reasons for this failure: Babbage was such a perfectionist he was quite unable to moderate his ambitions; and he was soon conscious of the structural limitations of his Difference Engine, which made him gradually lose interest in it in order to devote himself toa far more ambitious project which we shall come to presently.

The first time the conception was completely realised was in 1853 whenthe Swedes Georg and Edvard Scheutz, inspired by Babbage's work, constructed a sturdy and dependable difference machine with financial support from their country; it worked satisfactorily and had the facility to print out results. (Be it noted in passing that the Scheutz brothers' machine was the first working calculator in history that did print out theresults.)This achievement was soon followed by several others, starting with that of the Swede Martin Wiberg, who in 1859 produced a more compact machine endowed with additional capabilities, then by those of the American George Grant (1871), the Frenchman Leon Bollee (1895), the Irishman Percy Ludgate (1905), the German Christel Hamann (1910),and others.

BABBAGE'S FIRST IDEA PROVED A DEAD END

However, this type of machine never enjoyed the success of the classic mechanical calculators. Their importance diminished, moreover, from the early 1920s when it was realised that their functions could be fulfilled both by the multi-register accounting machines (see pp. 151ff.) and by mechanographical punched-card machines (see pp. 179ff.).

Itwas the principal defect of the difference machines that explained their failure: like the belfry automata, the astronomical clocks, and the earliest automatic carillons, their control systems were mingled with their calculating mechanisms. Their control systems were part and parcel oftheir inner workings and not independent from the material structure of the machine. Worse still, these calculators lacked versatility, restricted as they were to a single type of calculation (those based on the method of finite differences); furthermore, the control system needed to be reset for each new sequence of calculations.

In a word, the difference machines were digital sequence automata basedon a fixed control system that could not be modified. Their rigidity led to a dead end.

THE FIRST SEQUENTIAL AUTOMATA CONTROLLEDBY A MODIFIABLE CONTROL MECHANISM

And yet the first solutions to this problem had already reached Europe bythe end of the fifteenth century with the appearance of the first automatic carillons controlled by interchangeable mobile drums with pegs, like the one built in 1487 by Barthelemy de Koecke at Alost in what is now Belgium, or the Speeltrommel Carillon built in 1666 at Utrecht in the Low Countries.

Thus this development clearly marks the earliest appearance of sequential automata controlled by a modifiable control unit.

THE FIRST PROGRAMMABLE SEQUENTIAL AUTOMATA

These solutions, however, continued to be quite inadequate, because eachadditional sequence involved the construction of yet a further control unit.
But with the great advance in clockwork and high-precision technology in Europe, far more elaborate solutions were developed in the eighteenth century when the Frenchman Jacques de Vaucanson, the Austrian Friedrich von Knaus, and yet others built their famous android or animal automata.
Each one of these automata was equipped with a mechanism controlling the instructions needed to execute a given sequence of basic operations,
thus prefiguring the modern concept of programming.

BABBAGE'S ANALYTICAL. ENGINE:
A TRUE ANCESTOR OF THE PRESENT-DAY COMPUTER

In fact Hollerith was not the first to apply the system of programming using punched cards in a digital machine. The English mathematician Charles Babbage had done it far more successfully half a century earlier. This point is vital if we wish to emphasise the fact that this scientist was in many ways the grandfather of the modern computer.

Going much further than his "difference engine", this one was designed to enlarge considerably the scope of artificial calculation. Until his death,
Babbage devoted himself body and soul to perfecting an extremely complex calculating machine which he called his Analytical Engine. To form an idea of the strong impression that this machine made on the inventor’s contemporaries and immediate successors, it is sufficient to cite Mauriced'Ocagne's account of 1905:

With the machine we are now going to discuss, we seem to be entering into a magical realm. In the mind of the inventor, it was intended to carry out any series of arithmetical operations on any numbers, in as great a quantity as desired, and to provide a printed solution accompanied by an algebraic explanation of the operations that had been carried out.

At first sight, the mind retreats in horror at the very terms of the problem and dares not even entertain the possibility of there being a solution. It was nevertheless onto looking for just such a solution that Charles Babbage began to concentrate all his efforts in 1834and, a few years later, he managed to overcome at least theoretically all of the difficulties raised by the question.

We should not smile at this. For that time, the mere idea of a machine ofthis sort was most impressive. Babbage's machine was designed theoretically between 1834 and 1836, and was equipped with a control unit with moveable sprockets on a cylinder that could be modified, and with 1,000 registers of 50 digits. It was structurally conceived to carry out automatically sequences of linked operations, of any arithmetical or algebraic variety, simultaneously on its one thousand 50-digit numbers. The power of the Analytical Engine's mechanism was thus supposed to cover the entire range of numerical and algebraic relations.

Babbage expressed his own astonishment at his discoveries and innovations in a letter that he sent in May 1835 to his friend, the statistician A.Quetelet: "For the last six months, I have been working on a machine that is more powerful than the first [the difference engine]. I am myself surprised at the power that can be conferred on this new mechanism. Just one year ago, I should never have imagined that such a result was possible."

But, apart from a few minor modifications, the general architecture of the Analytical Engine was fixed for good some five years later. To cite Maurice d'Ocagne again:

As of 1842, General Menabrea, then a captain in the Piedmontese engineers, was able to give an initial description of the machine, based on Babbage's explanations, in the Bibliotheque universelle de Geneve(XLI, p. 352). A curious fact should be noted, which General Menabrea mentioned to the Academy of Sciences in Paris when he presented the machine to them in 1884 (see CRAS, 2nd week 1884, p.179). His paper had been translated into English for Taylor's Scientific Memoirs(see vol. III, London, 1843). The translator, who had signed only with the initials L.A.L., had added notes that displayed a remarkable insight and great mathematical culture, and at the same time a profound knowledge of the subject. Intrigued, Captain Menabrea asked Babbage to reveal the secret behind the initials.

How surprised he was when Babbage gave him the name of Lady Ada Lovelace, Lord Byron's only daughter. It would be hard to imaginea greater contrast between the poet and his daughter, who had applied herself to the exact and extremely arduous study of calculating machines.

This is indeed all the more strange when, through the magic of words and metaphors, this lady mathematician transformed the driest mathematical formulae and the most off-putting technical descriptions into the most exquisite algorithmic poems. As she put it in her text: "We can say that the Analytical Engine will weave algebraic patterns, just as Jacquard looms weave flowers and leaves".

Ada Augusta Byron, Countess Lovelace (1815-1852), was also the first weaver of coded instructions on punched cards. She had devised a certain number of programmes with the idea of one day introducing them into the machine of her friend and master. They were based on a language that was compatible with the Analytical Engine, which she had adapted from the very system of punched cards that had been invented by Basile Bouchon, and subsequently perfected by Joseph-Marie Jacquard.

"She was a woman of some ability, and she had a clear grasp of her subject. If the Analytical Engine had been built, she would have been perfectly qualified to be its chief mathematician." [M. V. Wilkes (1956)
pp. 10–I1] But figures of rhetoric were not enough and, with her great precision and extraordinary insight, Ada Lovelace brought up the epistemological problems that were to arise: "The Analytical Engine has no claim to originate anything. It can carry out anything it is told to do. It can

follow an analysis, but it is incapable of imagining analytical relations or truths. Its role is to help us carry out that which we already master."

It must be said that, in its inventor's own view and according to his own terminology, Babbage's machine was equipped with:

1 an input/output unit;

2 a unit for setting the machine in motion (for which Babbage did not coin a term), which transferred the numbers from one section to another in order to place them in the correct sequence: it was the machine's control unit;

3 a store, which was a numerical memory capable of storing the intermediate or final results of the calculations that had been carried out: it was the machine's memory, able to receive the numbers used in the calculations and store the results;

4a mill, which was designed to carry out the operations on the numbers that had been introduced into the Analytical Engine: this was the machine’s arithmetic unit, in which numbers were combined according to the required rules — in other words it was the processing unit whose job it was to carry out the calculations by employing the data that had been introduced into the machine and transforming it in order to produce the desired results;

5 finally,a printing device to provide the results.

Thus Babbage's machine was, at least on paper, a true predecessor of modern computers.

In the history of automatic and sequential digital calculation, the great synthesis had thus been achieved by this inventor of genius, who succeeded in applying not only the progress that had already been made in the mechanisation of arithmetical calculation (contributions of Leibniz, Leupold, Stanhope, Thomas of Colmar, etc.), but also the discoveries of the great constructors of mechanical automata during the Enlightenment(Von Knaus, Vaucanson, Jaquet-Droz, Kintzig, etc.), as well as the conceptions of Joseph-Marie Jacquard, the period's greatest programming expert.

Approximately one century ahead of his time, and at a period when such conceptions were difficult to understand, Babbage thus clearly defined the main units and functions of analytical calculators (see pp. 202-3).

Since Babbage’s machine required no human intervention in the carrying-out of its sequences of operations, it thus also synthesised the concept of an automatic sequential digital calculator with a non-cyclical automaton governed by a flexible programming system and equipped with a modifiable control unit, independent of the material structure of the corresponding internal mechanisms.

Even more importantly, Babbage defined, for the first time in history, a true precursor of today's universal computers: general-purpose analytical

WHAT IS AN ANALYTICAL CALCULATOR?

Before proceeding, we should first clarify what these terms mean.

Itwill be noticed that this expression is as old as Babbage's engine itself. And yet, it still appears new because historians of the computer have never made proper use of it. The word "analytical" derives from the Greek analusis, from the verb analuein, which means "to untie", or "release" apart from the whole, including the most elementary parts. It is thus identical with the analytic method in mathematics, which consists in" reducing a given problem to a second problem, the second to a third, and so on, until we arrive at a problem we can solve"(J.M. Duhamel, Methodes dans les sciences de raisonnement, I,p. 51).

Now, this is the precise meaning of numerical analysis, which is abasic part of automatic digital calculation. Its aim is to study practicalways to solve mathematical problems numerically and to refine them bymeans of appropriate techniques. Thus, in Condillac's words: "to analyse is to decompose, to compare and to understand relations . . . Analysis is thus the total decomposition of an object, and the distribution of theparts in an order such that generation becomes easy" ("Art de Penser", Oeuvres philosophiques, I,p. 410).This method is therefore the opposite of the synthetic method, which consists in deducing from a problem which we can solve the solution of the preceding one, which we then relate to the original problem, and then the solution of the one preceding this, and so on until we find the solution of the original problem itself(see J.M. Duhamel,op.cit.).

Now, analytical was precisely the term Babbage chose for his engine, which was thus the first analytical calculator to be conceived by a human mind. And, after Babbage, Torres y Quevedo continued to use the same term in his Essays for the Automatic, when studying "the general principles applied to analytical engines". In other words, even if Babbage did not exactly express it in these terms, he had invented what may be called analytical calculation. This consists in:

1 a preliminary investigation of any given problem of a solvable category to reduce it to a second problem, then to a third, and soon, in order to determine the mathematical rules and procedures needed to solve it;

2 the application of these rules and procedures by means of a programme of instructions in an appropriate machine;

3 finally, the problem is solved by the machine itself which, controlled by the programme, automatically carries out sequences of instructions, rigorously in the order of the various elementary steps defined by the procedure.

In terms of automata, the general definition of calculators based on thistechnique is as follows: an analytical calculator is a digital, sequential andprogrammable automaton:

•which is governed by a flexible programming system;

•which is equipped with a modifiable control unit, independent ofthe material structure of the machine's internal apparatus;

•and which necessitates no human intervention in order to carryout completely the sequences of programmed instructions to beexecuted.

This general definition (in modern terms) indeed corresponds toBabbage's machine. It also allows us to isolate the true concept, as a sortof algebraic structure independent of whatever technology is being used.
Since it also clearly displays the potency of Charles Babbage's synthesis,
itwill also now be easier to see the difference between this machine andthe belfry automata, astronomical clocks, automatic chiming bells orVaucanson's and Jaquet-Droz's androids. What is more, it allows us to havea better understanding of the basic difference between the AnalyticalEngine and rigid, inflexible calculators in the classic categories of account-
ing machines, mechanographical and analogue calculators or those relatedto the difference engine (see pp. 169ff.).

THE INCONTESTABLE INFLUENCE OF BABBAGEON RESEARCH BETWEEN THE WARS

To return to the history of analytical calculation, even though peoplehave sometimes abbreviated it (to magnify their own glory or else, in anot always disinterested manner, to highlight a particular local or nationalcontribution), it must be said that all of the research carried out at thattime was inevitably influenced in one way or another by Charles Babbage'swork. Ideas such as his are certainly not found overnight. It can beobserved that most of the treatises and articles dealing with digital calcula-

tion by means of artificial or mechanical means that were published inthe nineteenth century and the early twentieth century contain the veryideas that constituted Babbage's Analytical Engine. This applies equallyto instructionmanuals for researchers, or sources of information orinspiration concerning theories of automatic calculation that had alreadybeen more or less developed.

Among such publications, we can cite:

•the work of Maurice d'Ocagne (previously extremely well known,
and republished several times after 1893);

•that of L. Jacob published in 1911;

•the important articleNumerisches Rechnenpublished by R. Mehmke