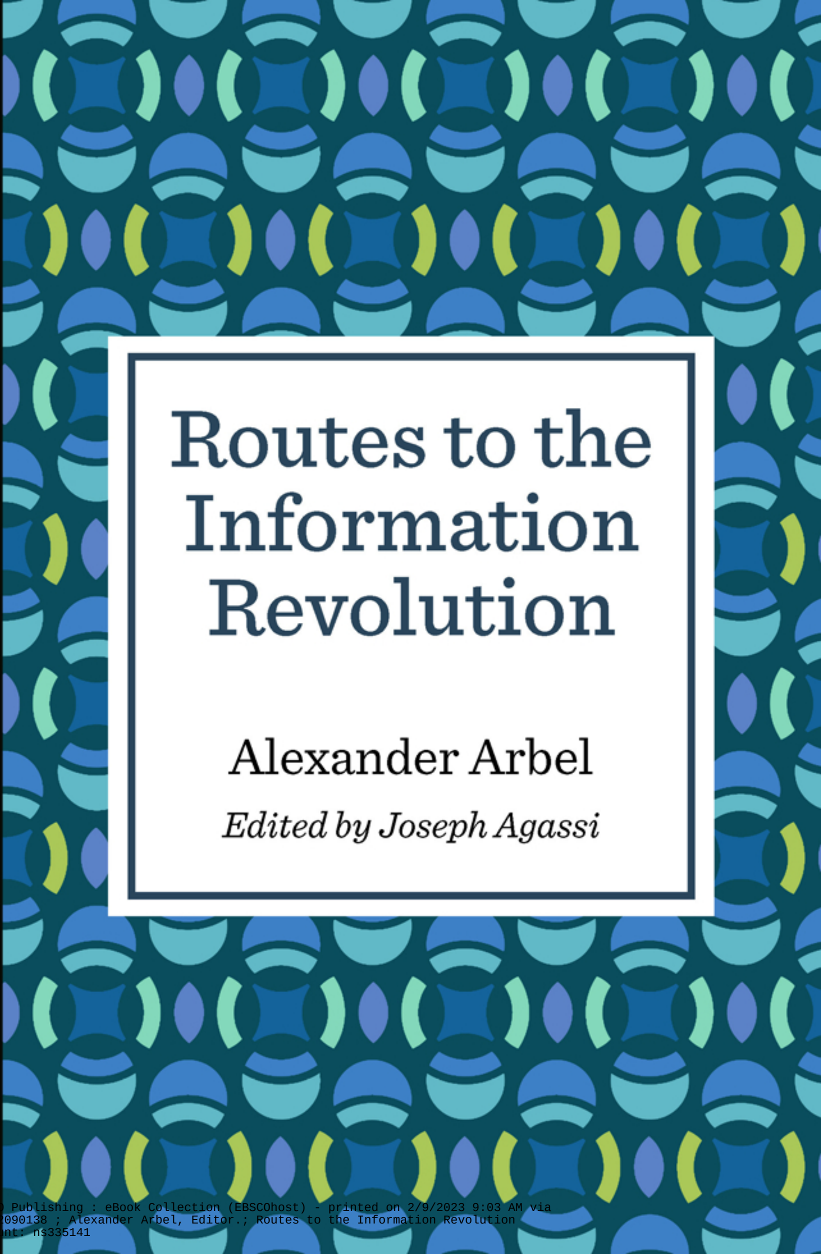

Routes to the Information Revolution

Alexander Arbel

Edited by Joseph Agassi

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PREFACE

Scope

The roots and routes of the digital computer are presented here with an examination and analysis of commonly accepted views of the history of digital computing and while seeking alternative scenarios and paradigms of the development of the digital computer, applicable also to the history of technology in general.

The question examined here is: Why were automatic digital program-controlled calculating devices developed simultaneously in Germany, the USA and the UK during the period 1935-1945?

What is so astounding is how every technology, idea, calculating means and calculating technique existed and were available long before the development of the automatic digital program-controlled calculating devices discussed herein took place. Yet, only during the period 1935-1945 did they materialize. Efforts to develop this type of device had already been undertaken and accomplished before by Babbage (1834) and Ludgate (1909). Nevertheless, these devices were brought to fulfillment and practical use only in the period 1935-1945, by a group of developers ignorant of the work of their brilliant and forgotten predecessors. This is our point of departure.

Layout

Readers who have no formal background in the history of the computer or computer science should find little difficulty understanding the discussion in the current work. It is written in consideration for the convenience of the lay reader unfamiliar with computing history. Therefore, the current work is supported only by the minimum necessary technical knowledge and jargon. In the rare cases in which excessively professional or technical terms are employed, they are defined and explained within the text. Moreover, I strive to produce a digestible text while concentrating on essentials, in as simple and explicit language as possible, in order to be clear to everyone, comprehensible even to my own children who served as my test readership.

As the amount of material in the current work is extensive and may seem at first glance too technical, I have made a serious attempt to make each portion relatively independent of the others. Hence, this discussion is modular. In this way, readers can choose or skip any portion of it.

The book is divided into three parts:

Part I deals with prehistory, the preface and historical background, focusing upon the description of devices, components and techniques available before 1935. Despite the happenstance that these components were indeed incorporated as part and parcel of the new automatic program-controlled digital calculating machines, nevertheless, these components in and of themselves cannot be classified as automatic program-controlled digital calculating machines or computers. Thus, seemingly essential as such background may seem, if it is too lengthy and technical it may readily be skipped without loss of continuity.

Part II deals with the period 1935-1945; it is the gist of the current work and contains a great deal of new material on the individuals who participated in the development of the automatic digital program-controlled calculating devices during the period 1935-1945 in Germany, the USA and the UK, and is most openly disputable because new historical information needs time in order to be digested critically within the field for accuracy and reliability and for better understanding of their implications. Here the discourse focuses on collective and individual biographical portraiture of all those developers around the world. Here I examine and analyze why they did what they did; what the relations were between their educational background, their work and occupation and the formalization of mathematics, and the appearance of the automatic program-controlled digital calculating machines: computers. Of greatest importance and interest is the ongoing controversy between fourteen alternative answers put forth by others and by myself to the above standard historical questions.

Part III deals with the period after 1945, serving as an epilogue to the current work, linked only indirectly to the central question of the present work: What were the end results and the byproducts of those developments and how did they become unified? In other words, when did the various developers become aware or know that they were dealing with the same object? The module deals briefly with the after-effects of the developments of the period 1935-1945 without sliding into philosophical approaches to technology as such, or worse, all too common preaching thereupon.

Topics of interest are catalogued in Appendices A and B, the former dealing with the evolution of the nomenclature and concept of the computer, and the latter dealing with the issue of the stored program concept and with von Neumann. Appendix C is an extended index of the people involved in the development of calculating means during the last five hundred years.

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Professor Funkenstein was of great influence to my historical approach, affording balance between the traditional linear and continuous concept and my own tendency to see the history of the computer as discontinuous with previous traditions and events.

From Professor Agassi I adopted the conduct of debate by posing questions and explicitly offering as many as possible different alternative competing answers to any question. Later on, arguments and information are brought to bear in efforts to refute the alternative answers, in a process of elimination, thus narrowing, reducing the number of viable alternative answers, and focusing on them. Therein lies my attempt at a meaningful contribution. Moreover, this method transformed the often wearisome toil of writing a multitude of details into a pleasant and exciting experience.

Professor Yehoshafat Giveon helped me a great deal not only in attention to wording and explication, but by helping in focusing the debate upon the very concept of the computer in deeper understanding as to what we really know about what these pioneers in technology were thinking as they accomplished their great work.

I am deeply indebted to all three of my mentors for their specific ideas and criticism.

I take this opportunity to publicly thank the following scholars, computer developers and computer pioneers for their good will and courtesy while discussing with me their work at some length: Professor K. Zuse, Professor Wilkes, Professor Burks and his wife Alice, Professor B. Galler, Professor Stibitz, Dr. H. Goldstine, Professor J. Atanasoff, Professor B. Oettinger, Professor I. B. Cohen, Dr. P. Ceruzzi and in particular Professor J. Gillis.

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Alex Arbel

N. B. In my editing the final version of this study I received assistance from Alex Monaghan of Imprimatur Editing and from Raz Arbel, grandson of Alex. All errors added to the text by my editorial decisions are my responsibility, of course. I have refrained from commenting on the text or adding to it (except for minor additions, mainly clarifications, and a brief comment on his Answer 5 at the end of its text and before the endnotes). Readers interested in my views on other items are invited to consult my 1985 *Technology: Philosophical and Social Aspects* as well as my 2008 *Science and Its History: A Reassessment of the Historiography of Science;* my 2018 *Ludwig Wittgenstein's Philosophical Investigations: An Attempt at a Critical Rationalist Appraisal* includes discussions of the rise of the very idea of formal languages.

Joseph Agassi

INTRODUCTION

My aim here is to identify the causes that led to the multiple, simultaneous appearance of the automatic program-controlled digital calculating machines (the forerunners of the digital computers) in the USA, Germany and the UK during the period 1935-1945. I will focus here upon the development of six design models of such devices (automatic program-controlled digital calculating machines) that were completed for actual use. I will also discuss several proposals and designs that did not materialize or come into practice. I have intentionally avoided the use of the term 'computer' for this class of automatic program-controlled digital calculating machines, because the term 'computer' does not take root before the 1960s. The term 'computer' will be limited here to indicate the general discipline under discussion, i.e. the history of the digital computer.

Explication of Nomenclature, Terminology, Concepts and Notions

First let us determine the meanings of 'term', 'concept' and 'notion'. Here, 'term' defines the plain literal meaning of a word or expression, as opposed to 'concept' or 'notion', which define how this word is grasped by our minds.

As the present study presents attempts to identify the theoretical and technical factors that may have led to the multiple and simultaneous emergence of the automatic program-controlled digital calculating machines in Germany, the UK and the USA during the period 1935-1945, to indicate the general discipline under discussion, i.e. the history of the digital computer (for details, see Appendix A).

In the history of technology, as in other domains, there are many examples of simultaneous and multiple discoveries, meaning the phenomenon in which, during a relatively short period of time and in parallel, more than one person reaches, independently and separately, a discovery that we later tend to see as identical, multiple or congruent. I will also use here the terms 'multiple' and 'parallel' to portray such phenomena. 'Multiple' refers here to the manifold and parallelism of inventions; 'simultaneous' tools in parallel, at the same time.

The terms 'device', 'machine', 'instrument', 'tools', 'engine' or 'apparatus', used in conjunction with the adjective 'calculating', are used synonymously and alternatively, though one can find clear distinctions between them. In accepted common terminology, a 'device' is an artificial auxiliary instrument or accessory aimed to assist a person and lighten work and to extend the functions of the human body. However, while it may have a slight connotation towards the term 'tool', a device nevertheless differs therefrom. I will not deal with this difference here, because it involves a deeper discourse on the problem of technology that I will define as human *artificial extension of bodily functionality*.

The terms 'component', 'element', 'unit' or 'apparatus', used in conjunction with the adjectives 'storage', 'calculating/computing', 'input/output' and 'control', are used synonymously and alternatively as well.

I also prefer to use the expression 'calculating machine' (or 'device', etc.) rather than the term 'calculator', as this may cause some confusion with a human calculator, an employee having the profession of performing computation-reckoning. However, the term 'computer' was in use even during the 1940s to designate human computers.

The word 'machine' is derived from the Greek word *'mechane'*, meaning an installation or a structure in an idol's image. A machine is an apparatus combining primary components intended to carry out work by saving time and power. Though there is a distinction between these two terms ('machine' and 'device'), an analysis of these terms 'device'/'tool' or 'machine' reveals an exaggerated stress of the process, and the existence of a deep disagreement about what belongs to this process. Occasionally, such perceptions are accompanied by arguments that the process of progress is inevitable-compulsory or deterministic. Such answers are examined here.

I prefer the term 'development' and 'developers' to 'invention' or 'inventors' because it is extremely difficult to determine exactly who invented what. I reckon 'invention' as a legal term and therefore subject to debate according to the different patent laws in various countries. The term 'development', although also subject to various interpretations and controversies, is less contentious and enables more fruitful debates. The stage of technological development is the one when the model of the prototype of an abstract idea is designed and built. The development process may take various forms which involve the adaptation and merging of ideas to the different tools, components and materials available prior to, or created during, the development process itself.

Explication of the Term 'Automatic Program-Controlled Digital Calculating Machines'

The term 'digital calculating machines' indicates that the data processing (calculation) is carried out in such devices mechanically by an artificial means on a discrete, unique arbitrary numerical basis, utilizing one or more of the basic arithmetic operations: addition, subtraction, multiplication and division in a manner similar to that of the 'human computer' (a term that would have been redundant prior to the mechanization of the task) used by Alan Turing in his famous paper from 1936, 'On Computable Numbers'.

The devices are automatic, meaning they operate independently of any human intervention from the beginning of a defined task until its completion according to the required process.

The program-control faculty enables the device to change and adapt its operating mode without alterations in their physical structure, thus giving them a capacity that is general or multi-purpose, to imitate any final defined algorithm.

The common denominators of the particular types of this device, in development during the period 1935-1945, are the following components:

a. The digital component, on an arbitrary number basis representation.
b. The numerical data storage component for keeping the numerical data required for the calculating process.
c. The program storage component for the storage of program commands.
d. The control component for a general and multi-purpose capacity.
e. The input and output components for creating the man-machine interface in order to input data into and retrieve data from the machine.

Focusing on the Period 1935-1945

This study focuses upon the period 1935-1945 because this type of machine did not exist before 1935, while after 1945 John von Neumann, in the paper 'First Draft of a Report on the EDVAC' and the paper written by him in 1946 with Arthur Burks and Herman Goldstine 'Preliminary Discussion of the Logical Design of an Electronic Computing Instrument', determined and published the unique characteristics and specific definition which distinguished these calculating machines from all others [1].

Focusing on the Location of the Events

This study focuses upon the USA, Germany and the United Kingdom because only in these three countries did a comprehensive development of this type of machine (automatic program-controlled digital calculating machine) take place, and only there were they applied to computation and information processing.

In the USA, during that period, two vacuum tube-based electronic machines were developed, one at the University of Iowa, the other at the University of Pennsylvania. Also, two electro-magnetic machines were developed, one at Bell Laboratories and one at IBM Laboratories in collaboration with Harvard University.

In Germany at that time several mechanical, electro-mechanical, electro-magnetic models were developed and even an improved vacuum tube-based electronic instrument was designed and constructed.

Simultaneously, in the UK electro-magnetic and electronic devices were developed for the purpose of code deciphering, though similar instruments were also built in Germany and the USA.

Evidence suggests that instruments of this type were also designed and developed in France at that time. However, these were only on a theoretical design level, despite an agreement signed with a well-known manufacturer of calculating machines to produce of one of them. World War II disrupted the plan before it could be carried out.

Main Issues

I focus upon several issues that have not yet been adequately dealt with elsewhere:

1. The matter of simultaneous and multiple discovery. I examine whether the devices discussed here are identical, similar or approximately the same, or whether we are dealing with machines of different kinds. The definitions and criteria of the machines are examined. The logical distinction between identical and different is obvious. There is, however, a logical difficulty in distinguishing between 'similar' and 'like'. I chose to define 'similar' as a term deriving from geometry, i.e. similar bodies are those that have identical forms yet their sizes are proportionally different from each other; similar figures are figures that have the same shape; photographically one is an

enlargement of the other. For the present discussion, this will be expressed as different scales of their characteristics.

2. The evolution of the discoveries. I pursue the origins of those devices and examine whether the digital computer is an outcome of a long tradition that started with the wheel as a tools for counting, or whether it constitutes development of several specific technical traditions of counting, of digital and analogical measurements, of abstract logic and computing traditions. Or, whether we are dealing here with a development that constitutes a break with other, former traditions. If this is so, how can such a leap forward or rupture in previous continuity be determined?

3. The timing. Why were these automatic program-controlled digital calculating machines developed specifically during the period 1935-1945 and not before, even though the necessary components were already available?

4. The 'Babbage Affair'. How does one explain the design of an Analytical Engine that fulfills all the required criteria for such instruments as the automatic program-controlled digital calculating machines, in 1834, i.e., one hundred years before their 'invention'?

5. The 'geographic' question. Why were these machines developed only in the USA, the UK and Germany (and France) and not elsewhere?

6. Why did this group of developers choose to apply 'binary technology' and no other, e.g., electro-magnetic or the mechanical or vacuum tube technologies?

7. Was this group of developers unique? What type of problems preoccupied them that they tried to solve and that they actually succeeded in solving?

8. The influence of World War II. What were the effects of the preparations for the war and the war itself on the emergence of these automatic program-controlled digital calculating machines and the computer?

Existent Literature

Until recently, the automatic program-controlled digital calculating machine was perceived as an American invention. Moreover, no serious attempt has been made to examine historiographically the problem of why the history of the digital computer was written in the manner that it has been. Most of the studies published analyze the events that led to the development of a specific instrument or compare the development of technically or conceptually related instruments. The history of the digital computer has been told as an aggregate of single occurrences that merge into a continuous and linear chain of events, rather than as a confluence of favorable circumstances. The chronology was arbitrarily determined to have begun sometime in the past, say, with Pascal (1642), Leibniz (1671), Jacquard (1804), Babbage (1822), Boole (1854), Hollerith (1880), or Aiken (1937), and to have ended with the so-called ‘First Draft of a Report on the EDVAC’ of von Neumann (1945), and the publication of an article which I have called the ‘Trinity Paper’ in 1946. (This is a nickname that I gave to the report prepared within the framework of the conditions of a contract between the Research and Development Division of the US Army’s Ordnance Department and the Institute for Advanced Studies, Princeton. The full title of the report, by Burks, Goldstine and von Neumann, is ‘Preliminary Discussion of the Logical Design of an Electronic Computing Instrument’, dated 28 June 1946.) The appellation ‘Trinity’ has a dual meaning: it indicates that it was written by the three aforementioned persons, who had decided to build their own computer at Princeton, and also that, like Holy Writ, the paper commanded blind obedience on all further developments of the computer.

Thomas Smith (1970) was the first to come out against the linear approach in the writing of the history of the computer and claimed that the modem computer is the result of the convergence of several technical traditions that influenced each other throughout the centuries [2]. Smith claims that these traditions reached the peak of their influence on mathematical calculators during World War II and, as a result, large-scale digital and analog machines were constructed.

Herman Goldstine (the US Army supervisor of the electronic computer project ENIAC at the University of Pennsylvania during 1943-1946), in his book, *The Computer from Pascal to von Neumann* (1972), adopted a stance similar to that of Smith [3].

Nancy Stem, in the first doctorate (1978) ever to be written on the history of the computer, and in her book (1981) based on that dissertation, *From ENIAC to UNIVAC: An Appraisal of the Eckert-Mauchly Computers,* focuses upon the institutional history of computer development carried out at Pennsylvania by Eckert and Mauchly during 1943-1950. Stem points out that during the war, the military administration was more inclined to trust individuals who had put in requests for more money than to listen to the advice of experts regarding the feasibility of the various proposals [4].

Wells, in his doctoral dissertation (1978) on 'The Origins of the Computer Industry: A Case Study in Radical Technological Change' [5], states that the electronic computer was economically worthwhile and that with the tools then available it was impossible to achieve a sufficient rate of production of artillery firing tables, despite the more intensive use of ordinary calculating machines or human computers. Like Stem, Wells claims that during wartime people tend to be more open-minded, and there is a greater readiness to allocate resources for radical innovations, such as ENIAC, in order to solve urgent problems.

Paul Ceruzzi, in his doctoral dissertation (1980) 'The Prehistory of the Digital Computer, 1935-1945: A Cross Cultural Study' and the book (1983) based on it, *Reckoners: The Prehistory of the Digital Computer, from Relays to the Stored Program Concept, 1935-1945*, compare four developments carried out in Germany and the USA prior to and during World War II [6].

On the other hand, B. O. Williams in his doctoral dissertation (1984) is concerned with the interrelations between the analog and the digital computer, and their influence on the emergence of the electronic computer, ENIAC, at the University of Pennsylvania [7]. Basing himself on Goldstine, Stem and Ceruzzi, Williams examines some of their conclusions such as 'the ENIAC was a radical innovation and a daring gamble'. According to Williams, the ENIAC team based its work on previous developments that had occurred elsewhere, at RCA, NCR, and particularly at MIT.

William Aspray's doctorate (1980) focuses on 'the origins of computer science in that branch of mathematical logic known as recursive functions theory.' [8]. Aspray claims the inception of a new discipline of recursive functions evolved as a reaction to a fundamental crisis that occurred in mathematics. These functions permitted the creation of practical formalism for the calculation of various functions that had previously been not computable. The recursive functions thus established the theoretical basis for computer science. Aspray starts out with the program of David Hilbert (1862-1943) of 1900, refers to Kurt Gödel (1906-1978), Alonzo Church (1903-1995), John Barkley Rosser (1907-1989), Stephen Cole Kleene (1903-1995) and focuses on Alan Turing (1912-1954) and John von Neumann (1903-1957) and their conceptual contributions to computer science.

Thomas Park Hughes (1975) favors the 'reverse salient' claim, i.e., invention during the process of overcoming critical problems, as the explanation of the development of ENIAC, stating, 'as early as 1930 forces were at work setting the stage for its appearance.' [9]. Hughes suggests that the ENIAC team invented a computer with a uniquely designed accumulator (counting and storing element/component). This critical problem of an electronic accumulator was later solved in a breakthrough. Hughes claims that the origins of ENIAC are to be found in an analog instrument (differential analyzer—similar to Williams' claim). The 'reverse salient' approach rests on necessity or need, i.e., technological development derives from 'bottlenecks' that constitute limiting factors that are then challenged by the inventors. As the saying goes, 'Necessity is the mother of invention.' Although worded differently, Hughes' claim also expresses the continuous development approach in the history of technology in general and in the history of the computer in particular. The necessity or inevitability approach is exemplified as follows: 'The computer was waiting around for someone to need it. People were inventing parts of computers for very good purposes, although they did not have the idea of a general purpose computer or anything like it.' [10].

Guiding Ideas

The claims/arguments here rest on the following assumptions:

1. The simultaneous multiple developments of automatic program-controlled digital calculating machines during 1935-1945 in Germany, the USA and the UK constituted a break from the calculators already in existence.

2. The development of the digital computer resulted from changes in the concept and ideas of calculating tools. These conceptual changes derived from the emergence of the binary-discrete technology that gradually drove out the circular-continuous concept that regards the circle (wheel) as the principle enabling all logical activity. The emergence and growth of 'discrete technology', especially the binary technology in which only two distinct extreme conditions are possible, had a direct impact on the appearance of automatic program-controlled digital calculating machines.

3. The simultaneous development of automatic program-controlled digital calculating machines in Germany, the UK and the USA was founded on 100 years of parallel development that had been inspired by Ørsted's (1777-1851) 1819 experiment and by developments in certain technological fields such as electricity, electronics, machine engineering, wireline and wireless communication, applied mathematics and logic.

4. I have not yet found a decent explanation as to why these automatic program-controlled digital calculating machines appeared simultaneously during 1935-1945 in Germany, the UK and the USA. Of the eight machines discussed here, only one, the Colossus in England, was clearly the result of war activities. I tend to suppose that the timing of the development of ENIAC in the USA during the period 1943-1945 is debatable, regardless of the commonly held view that it was all a direct result of the war.

At this stage I would like to present two possible if admittedly hard-pressed elucidations regarding the timing of the inventions—developments—of the automatic program-controlled digital calculating machines:

a. At the beginning of the 1930s, calculating machines, punch and tabulating-equipment were widely used in business and management and gradually penetrated the academic world's installations. Engineers, mathematicians and physicists came to realize that mathematical problems can be analyzed instrumentally—an analysis which would allow a mutually balanced expansion of the application and formalization of mathematics for practical purposes in the fields of engineering and natural sciences.
b. During the 1930s, mass production of the complicated components required for the development of the automatic program-controlled digital calculating machines become reliable, accurate and reasonably priced. On the other hand, the rigid production and marketing policies of the calculating machines (including the punch equipment), manufacturers who concentrated on the business sector, and the high costs of the acquisition of commercial calculating equipment, as well as its limited adaptability to scientific calculations, hindered their widespread application in science and encouraged the development of tools with greater analytical capacities.

Attitudes and Stages of Technological Progress

A thorough examination of the biographies of the persons involved in the multiple and parallel development of the automatic program-controlled digital calculating machines did not reveal a kind of dichotomy between the so-called activities between the individual, social, or technological necessity formulated in wordings such as 'when the conditions were ripe or ready'. It seems to me that the history of computers presents a diverse type of the phenomenon that I will denote as 'development'. Although I dissent with contents of the definitions given in research for the term 'development', I may agree that development is one of the stages in technological change.

In the existing models of technological change, there is a distinction between invention, research, development and innovation.

According to the Stanford Research Institute Model, there are six main phases in technological development:

1. Discovery phase: The duration needed until a discovery/invention of an idea that did not exist previously.

2. Creative phase: The period between the discovery and the practical application of the new technology or the invention, sometimes also called the invention phase.

3. Substantiation phase: The period between the invention or the accomplishment of the technological configuration thereof and the beginning of a whole-scale development.

4. Development phase: The period in which the invention disseminates into other fields.

5. Innovation phase: The period in which major innovation cycles take place in a particular manner.

6. Business commercial acceptance phase: The period in which the new technology is combined and influenced by other branches of business cycles that contribute to its growth and distribution. Between phases 5 and 6 there is a strong affiliation, yet the model makes a distinction between them.

Gilfillan has shown that 19 inventions defined by him as the most useful in the period 1888-1913 passed through four different stages of development:

1. From conceiving the idea (discovery), up to the construction of the first practical working prototype (invention), there transpired 176 years.

2. From the construction of the first prototype and up to the practical application, an additional 24 years passed.

3. An additional 14 years passed until its successful commercial penetration.

4. 12 more years transpired until its penetration into other important applications.

In this model, Gilfillan included the electronic computer [11].

My assessment is that new technology is absorbed in three distinct phases:

1. Infiltration phase: The entrance of the new technology *via* the least resistant course and in those areas in which other particularly abundant and well-spread technologies provide poor opposition.

2. Consolidation phase: The integration and additional applications of the new technology in new areas by competitors, defeating previously existing technologies.

3. Dispersion and assimilation phase: New developments, ideas and applications spring from the new technology itself. This means that new development initiatives take place that were hardly possible earlier with only the previously existing technologies. This ranges from mere improvements, as in rather minor changes in application, to totally new concepts in the way things are done, which were impossible to envisage before the realization and assimilation of the new technology.

The development of steam technology may serve as an example. For almost one hundred years (from 1685), water was pumped from coalmines by steam. This pumped water was released on water wheels that set in motion various machinery systems in the mine. Around the year 1785 there was a move towards a direct use of steam engines as an energy production source for other tools. It was only during the 1830s that the steam engine increasingly supplanted the water wheel with such vigor and infiltrated all walks of life connected with energy operation on land and by sea. So, only then was it possible to have a motor driven lawn mower, tractor, car, or other product that had been unfeasible earlier, though the Frenchman Nicolas-Joseph Cugnot (1725-1804) of Lorraine, an artillery officer, had built a steam-powered tricycle in 1769, considered as the first automobile. In this sense there is a fascinating analogy between the development of the piston motivated engine and the digital computer. In the initial stage, huge machines (sometimes confused with large-scale) were constructed and were applied for existing tasks. In the second stage, there was a reduction in the size of these devices so that they gradually began their infiltration into a wider scope of fields of application. Then, at the final stage, miniaturization takes place, in which new technology infiltrates and assimilates into every possible area of our lives.

What is Development?

The historians of economics cultivated and focused upon the research of 'innovation', because they linked the emergence of tools, machines and new processes onto the market with innovation. By contrast, the historians of technology, interested in the research of technological change, have observed that inventors, engineers, promoters and entrepreneurs devoted most of their time and resources to a kind of activity that they call 'development', even though they have not defined this activity lucidly. According to William R. Hewlett (1913-2001; the co-founder of Hewlett-Packard and an American inventor who invented the 'Variable Frequency Oscillation Generator'), development is a phase between invention and innovation. 'Development … is an engineering enterprise. It demands, practical down to earth perspective which we attribute more commonly to engineers than to scientists.' [12]. This definition gives an absolutely clear distinction between science and technology. That is, technology as an applied or practical science.

What then is the meaning of the term 'development'? There is a widespread agreement among scholars that development is not invention, discovery or experimental innovation. Thomas Hughes has the following opinion: 'development is an activity occurring repeatedly in a complex sequence of ideas and events culminating in the use of new technology' [13]. According to Hughes, in many examples a means, tools or processes were unveiled to a renewed development phase, even after the innovation phase. This may indicate that technology functions and undergoes suitable modifications to fit the environment for which it was intended. He maintains that 'development is generally closer to environment in which technology will be used than are invention or research.' [14].

Hence, engineers applying common sense and practical experience particularly fit the development phase. Engineers are able to cope with great numbers of variables of the natural environment, or of those close to it, such as those that tend to prevent precise analysis and demand instead reliance on experience. This is also due to the manner in which development is closer in its goals to the habitat in which the technology will be implemented than research or innovation are. Therefore, the path from development to the evolutionist view is very short. 'Development is a continuous adaptation of the invention so that it will function in a more and more complex environment.' [15].

From this description we may conclude that development is connected to the adaptation of an artificial idea to its living conditions or habitat, while innovation is connected to the adaptation of the environment to the commodity; for example, the context of marketing policy and advertisement is connected to the history of the economy.

How can the development phase best be subjected to observation?

Did the development process have a definite pattern or form that can be detected? What kind of technology and tools were used there? Was the development there founded on intentional tools and ideas? Was development based on existing ideas, tools and technologies, or were intentional technologies, ideas and tools required for them? Was the trend of the development one of ongoing miniaturization (as with the steam engine and the computer, as cited above)? Did the development process involve a passage from individual activity to team work, or was that accomplished entirely individually? What kind of finance was involved, private, public or governmental? Was the development a result of a war or military market, or a result of research within the scientific and academic enterprise? What was the division between engineers and professional inventors as compared with scientists? Is it possible to trace regional or national styles and patterns or other patterns and paradigms?

By contrast to Thomas P. Hughes' and others' view, I do not suggest that the development process lends itself well to Darwinian analogy; that is to say, that the developer designs consistently resemble natural selection, survival of the fittest, as a response to the environment and the needs, and that all manipulations were intended to secure the survival of the meme-species. This seems to me to be only one of the possible alternative routes by which the development process may be conducted. The confusion here is, therefore, between what the 'development phase' is and how the 'development process' is carried out. These are two entirely different answers. My concern is to characterize the development phase and only then to determine how it is performed.

The primary technological development phase is characterized by the design and construction of the first concrete working prototype (more precisely, the archetype) of an abstract idea. The process of development that can be undertaken in manifold ways is characterized by the synthesis, combination and adaptation of ideas, materials, components and existing tools or those that may result from the development itself towards the design and construction of a concrete working model.

The Computer as a Multiple Discovery and Its Consequences

Up to now I have reviewed and examined some of the attitudes and answers available in current research concerning the phenomenon of multiple appearance of discoveries in order to apply them to the explanation of the multiple and parallel appearance of the automatic program-controlled digital calculating machines. [16] In the history of the digital computer, we can also clearly detect the adoption of two evolutionist approaches. The first approach rests on the tradition of linear depicting of continuity in the development of artificial calculating means from antiquity up to the present. According to this tradition, for example, the sticks and stones used by the prehistoric man for counting, measurement and fundamental calculations are considered as the computer of the Stone Age. The second approach claims that the history of the digital computer springs from the convergence of several parallel continuous traditions. The starting point in time and space, taken in these two evolutionist concepts, may seldom vary, but it is always arbitrarily set according to the interest and competence of the scholar.

Whereas previously the history of the computer was written essentially by computer scientists, it now serves as a convenient introduction with which to begin a book or a paper. Computer scientists occupied most of their time with problems of the present and the future surreptitiously rooted in the past of the computer history. Chronological data, such as who invented what and when, were prominent in the kind of history that has so long prevailed. For the typical history of technology served as the model that was imitated for writing the narrative account of the computer. To put it mildly, the data and accounts in the various books about the history of the computer leave the impression of veritable serial reproduction and copying one from another. The period of 1935-1945 is considered in research as 'prehistory', metaphorically and figuratively, an era ruled by gargantuan 'dinosaurs', those first machines, developed back then, notable for their sheer bulk. The metaphor condenms itself. In this sort of writing, no serious attempt was made to deal with the ideas that brought about the development of those automatic program-controlled digital calculating machines. The emphasis was set on portraying their properties and peculiarities. In prehistory, as it is known, there are no written findings, for we deal only with concrete items and objects. This is the niche set aside by computer scientists to the period that took place less than a generation ago, and we already face prehistory. Such a compression of timescales is only proportionate to the tremendous acceleration in computer development after 1945, shifting the focal point of the authors from the past into the present and the future. Another shortcoming and hindrance in the narration supplied by computer scientists is linked with the misplacement in time of the history of the computer. That is to say, they amalgamated notions and views of the 1950s and 1960s with occurrences that took place in the 1930s and 1940s. As an example, I will cite the use of the term 'computer'. In his (1973) *Selected Papers*, Brian Randell translates an extracted reprint from Konrad Zuse's Patent Application from 9 April 1936 whose title is, *'Verfahren zur Selbsttätigen Durchführung von Berechnungen mit hilfe von Rechenmaschinen'*. The English translation by Randell is, *'Method for Automatic Execution of Calculations with the aid of Computers'*. This is a mistranslation. In a discussion I held with Professor Randell at his home on 13 March 1987 on the writing of the history of the computer, I brought his attention, from a historical point of view, of the German word *'Rechenmachine'* into the English word 'computer'. He replied, 'The translation was carried out by a person considered expert in computer science in the UK'. I replied, 'This is evident and precisely the problem: if you turn to a computer science person for translation, you will get a computer-science person's translation'. It is obvious, even to the inexpert, that using the term 'computer' here rather than calculation-machine for *'Rechenmachine'* is anachronistic. Another issue is how Zuse, in those days, thought in terms of calculating machines as expressed and literally meant by the German term *'Rechenmachine'*, calculator. Thus, he searched for asses and found the kingdom, like Saul, sent by God to search for his father's asses when he was crowned as the first king of Israel (*Samuel I*, Ch. 9).

I have no knowledge of any similar precedent in the history of technological change, where the people of that era were at once so well acquainted, in the widest sense, with the arrival of a new technology, and so aware of confronting such radical and rapid alteration, indeed revolution. This is not to say that in the past people were not aware of changes brought about by technology, but what I emphasize here is the promptness, the reverberation and the extent of this dawning consciousness. Nevertheless, it is surprising that we were not wise enough to reach conclusions from the nature of previous technological revolutions, as in the case of the steam engine revolution. The steam engine caused, among other changes, alterations in the structure of social stratification, turning an agricultural society into a society that was in essence industrial. We observe the phenomenon and are aware that the computer revolution, as it is called by one of its designations, will change the structure of our present society from an industrial society to a leisure or service society. The direct effect of the first industrial revolution was an extreme decrease of employment in agriculture, from a very high percentage, around 90 percent, to a very low one; in the USA and Israel, for example, it fell to around 3 percent of the total working population. This is what has happened already in the industry of the developed countries since World War II. There has been a gradual decline in the number of employees in the industry and an increase in the number employed in the leisure and service sectors. The political and economic authorities refuse to observe these trends resulting in growing unemployment, trends that were so well noted by the political economists of the first industrial revolution, including Adam Smith, Malthus, David Riccardo, Robert Owen and others. It was the industrial revolution that brought about the public school of the compulsory education system. (In Greek the very word *'schole'* denotes leisure.) Nowadays, the intermediate period between childhood and adulthood is squandered, instead of, for instance, prolonging youth and maturing the duration of youth by extended education and preparation for adult working life even up to the age of 22. The advent of public school of the compulsory education system, like Sunday school hitherto, served to extend the period of childhood and reduce the presence of children in the labor market, necessitating vast public expenditures in unemployment allowances. But this fascinating discourse into the influence of technological change on society exceeds the scope of the present work. What has been said thus far must therefore suffice. I only hope to have veered away from falling into the trap of preaching, the vice of all too many books dealing with technology.

PART I

PREHISTORY

(THE PERIOD UNTIL 1935)

‘It is beyond the abilities of those—and they are the majority—for whom continuous evolution is the only paradigm of history: unable to cope with discontinuity, they cannot see it and will deny it right in the face. But such radical novelties are precisely the things technology can confront us with.’
(E. W. Dijkstra, ‘On a Cultural Gap’) [1]

CHAPTER ONE

SURVEY OF CALCULATING AUXILIARIES

Background

This chapter describes and scrutinizes the components, tools, ideas and techniques that existed until 1935, prior to the appearance of the automatic program-controlled digital calculating machines. It discusses different types of calculating tools, calculating instruments and other tools that are not considered as calculating instruments, and yet may have been integrated within the framework of the automatic program-controlled digital calculating machines. Though in this chapter the available calculating tools that were developed up to 1935 are brought about most of all, the author rejects the linear approach to the history of computers. That is to say, the automatic program-controlled digital calculating machines may have sprung, by some way, from older traditions of calculating tools that were developed in the past. The quotation at the heading of this chapter serves as guidance, emphasizing the discontinuity in the history of technology. I intend to show that the automatic program-controlled digital calculating machines appeared after 1935 in disconnection and oblivion to previous traditions of calculating tools [2]. Moreover, setting the final date of 1935 for conducting discourse on the then commonly accepted calculating tools does not rule out the possibility that after this date conventional calculating tools were not developed or improved upon. It only means that, after that date, whatever possible further usage and development of conventional calculating tools could no longer be relevant to our interest in detecting the causes that led to the multiple and simultaneous appearance of the automatic program-controlled digital calculating machines in Germany, the UK and the USA during the period 1935-1945. It seems evident that the conventional, common calculating tools and calculating auxiliaries that were built after 1935 could not have had any direct influence on the appearance of the automatic program-controlled digital calculating machines.

Up until 1935, several sorts of calculating auxiliary instruments that were applied to scientific, commercial and engineering computations were developed. In commerce, cash registers, desk calculating machines, and tabulating and punching equipment were all in widespread use for carrying out the sorting of statistical data and for accountancy. In gambling and race track betting, already by 1913, totalizators were introduced in New Zealand which were designed to indicate, in 'real time' (a term which was not in use back then, applied here anachronistically), the exact monetary values of the bets being wagered on any of the horses racing.

In scientific calculations, mathematical function tables were the most common auxiliaries in use. The application of office or commercial calculating tools such as hand and desk calculating machines or punch equipment for scientific calculations was in those days still the exception. For particular scientific measurements and calculations, specific or unique tools were usually designed, such as elementary particles counters, scanning equipment to find natural or special numbers and analog analyzers for scrutinizing and the summation of wave or periodical functions.

In engineering computations, the slide rule was the most common calculating auxiliary. However, office calculating machines, analog calculating tools, mathematical tables and nomograms (geometrical graphs for solving problems by the representation of mathematical proportions) were not entirely excluded.

The analysis of those method components that may have been incorporated in the automatic program-controlled digital calculating machines will commence with methods for the representation of numbers and quantities.

Methods for the Representation of Numbers and Quantities

Position Representation

In the decimal local position representation, the rightmost digit just indicates the amount of whole units in the number, the digit to the right of the decimal point enumerates the remaining tenths in the number, the next placed digit to the right enumerates the hundredths, the next the thousandths, and so on.

This technique of position/local representation took root in Europe gradually and with difficulty during the 12th century due to opposition presented by merchants. Its origin is Hindu-Arabic and it was brought from North Africa to Italy in 1202 by Leonardo Fibonacci (1170-1240). [3]

In the decimal base local representation, we have ten digits from 0 (zero) to 9 inclusive. The zero digit has a unique function: it serves to keep a place or to indicate that at that specific location the digit possesses no numerical value. In this manner the true value of the whole number is preserved. The term ‘zero’ derives from the Arabic *‘as-zifr’*, meaning empty or hollow. There is also a possibility that it is a corruption of the Hebrew word *‘sifra’*, meaning digit or numerical. [4]

The struggle over the introduction and the acceptance of the decimal numerical representation system in Europe was finally settled on the initiative of the Dutch mathematician S. Stevin (1548-1620; see Appendix A, ‘The evolution of the term and notion/concept ‘computer’).

In the numerical representation methods existing prior to the introduction of the Hindu-Arabic representation, fixed quantity values were attributed to symbols, as used for example in the Hebrew alphabet in which each alphabetical character has a numerical value. This use of letters as numerical values is called ‘Gimatria’, meaning numerology, in Hebrew and was used extensively in the Kabala as one of the ways for interpreting and finding signs of the secrets of divinity. The ancient Roman numerical system was also based on quantity symbol representation. In the Roman and Hebrew numerical systems, the quantitative value of the symbol is fixed and is irrelevant to its location within the number. This is to say that the same number can be represented in several options with the same symbols, because the numerical value and its representative value of each of the symbols is always constant regardless of its place within the number. The symbol quantity value method has at least two severe limitations: 1) it is awkward to perform mathematical operations/actions; 2) it is difficult to represent very large numbers, because long strings of symbols are required.

From a historical point of view, we can relate the quantitative representation to the concrete tradition of counting or enumeration, for example the counting of the years in the Hebrew/Jewish calendar. In contrast, the local representation is related to the abstract tradition which requires carrying out manipulations with numbers as abstract entities. Much as the manipulation of the alphabet’s characters enables the formation of strings of letters that represent, when provided with meaning, the words, similarly the arrangement and rearrangement of numerals enable the expression of any real number.

Digital Calculating Tools Available Until 1935

Tangible but not mechanical auxiliary calculators

Abacus

The first auxiliary tools used for recording quantities, which served as an intermediate medium for the storage of information, were the same widespread tool for recording other types of information. In the early ancient civilizations, the tools used for storing information were clay, papyrus, ropes, wooden planks, rocks, bones, stones and beans. Among the earliest auxiliary tools that assisted with carrying out calculations were small stones. One such mechanism was the abacus. The abacus is a digital calculating tool operating on the local representation principle. It has probably the longest historical tradition of calculating tools, appearing some 3,500 years ego. Extensive literature exists on the abacus, indicating that the use of this tool was then prevalent. Indeed, its calculating dexterity is remarkable.

The origin of the word ‘abacus’ is questionable. Some scholars are of the opinion that the word ‘abacus’ derives from the Greek word *‘abax’*, meaning a board or a leg-less table without support beneath. On this table were the calculating stones, the *calculi,* set up in a certain format that enabled calculations to be subsequently carried out. In Greek the meaning of the word *‘calculi’* in the plural and in the singular *‘calculus’* is gravel or water/river polished stones. The origin of the word *‘calculi’* is from the word *‘calx’*, meaning a grain of limestone and subsequently giving its name to the element Calcium. In antiquity, calculation teachers were known as *‘calculones’* if they were of slave origin; if they were of noble origin they were *‘calculatores’* or *‘numeraii’*. From the Greek word *‘calculi’* derive also the Latin word *‘calculare’* and the English word *‘calculate’*.

Another origin story of the word ‘abacus’ also claims that it derives from the Greek word *‘abax’*, that is to say, the calculation of numerical values according to their alphabetical order, i.e. $\alpha = 1$, $\beta = 2$, etc. There is also a claim that the word ‘abacus’ derives from a Phoenician or Semitic origin, such as the Hebrew word *‘abac’* meaning dust. On a given table, a thin layer of dust, powder or sand was spread on which numbers were inscribed and calculations performed in accord with a certain procedure.

The abacus (plural abaci or abacuses), also called a counting frame and which had been familiar in ancient Greece and Rome in the form of a calculating board, was re-introduced to Europe from the Far East in the 12th century in its modern form. Even so, the ancient form of the abacus was still preserved. Though, rather than counting stones, counting tokens, called 'zitons', were used; these carried images of the ruler. The tokens were set up in a special pattern along lines engraved on the board or marked on a piece of cloth. Subsequently, holes were drilled in the stones or tokens which were then threaded on a wire and fixed to a frame.

We can trace three distinct types of abacus: (i) the ancient abacus—the dust board, from which the name abacus also apparently originated; (ii) the abacus of calculi—stones—or counting tokens, which were placed on lines marked on a table or cloth; (iii) the final shape, known today, which had a number of beads threaded on wires fixed to a frame, which reached Europe in the 12th century, possibly from the Far East.

In summation, the abacus originated as a sand table for drawing, calculating, etc., and derives from the Latin *'abacus'*, from the Greek *'abax'* (genitive *abakos*), or 'counting table', from the Hebrew *'abaq'* (dust), from the root *a-b-q*, 'to fly off'. It was originally a drawing board covered with dust or sand that could be written on in order to perform mathematical equations. Specific reference to a counting frame dates to the 17th century or later.

Addendum: The word 'bank' was probably borrowed from 'bench' or 'counter'. Benches were used as desks or exchange counters during the Renaissance (1350-1600) by Florentine bankers, who used to make their transactions atop desks covered by green tablecloths.

Measuring devices (from Archimedes to the 12th Century)

Archimedes invented the wheelbarrow odometer (in Greek *'hodos'* means 'road' and *'metron'* means 'to measure') which was subsequently used to measure the distances marched by the Roman legions. The odometer applied the principle of counting the number of wheel rotations by means of a cogwheel gear mechanism and translating it into unit of distance—the Roman mile. The marched distance was marked mechanically by a special pointer on the wheelbarrow's surface. As the legion moved a soldier drove the wheelbarrow and the distance elapsed on the march was deduced according to the number of mile marks that appeared on the counter [5]. The odometer's cogwheel gear mechanism itself was nothing new. In ancient Egypt and Greece gearing mechanisms were well known [6]. The military architect and engineer Vitruvius, who dedicated to the Roman emperor Augustus his *On Architecture* that offers various versions of devices for sea and land distance measurements. Vitruvius has a description of single or two wheel carriages for measuring distances by means of cogwheel gear mechanisms of 1:400 proportions. One turn of the big wheel of the carriage measured one thousand *passus* (about 1700 meters) and gave a signal or knocked each time it crossed a Roman mile marking. There is also an example of a planetary system mechanism representing the Aristotelian solar system principle established more than 2,000 years ago, in which we can find a set of cogwheel gear mechanisms which operates in a manner resembling the spring operating timepiece [7].

In his odometer, Archimedes used the cogwheel gear principle to create proportions between the various wheels for an analogy of the distance elapsed and the transfer of the carry. The carry is that unique action performed each time after the completion of a defined number of wheel rotations. In other words, it is a method of perpetual counting that enables the increase of the stepping of the number of teeth on the neighboring wheel in the cog gear. The carry in calculations is that excess above 9 that we have to transfer to the next column to the left. Hence, we may claim that the uniqueness of the ancient odometer is not in utilizing the cogwheel gear mechanism principle as a power or speed ratio transformer, but as a tools to represent an analog model of the distance elapsed and, in particular, the introduction of the carry and markers for counting the number of rotations of this mechanism.

Contrary to the abacus which is a digital tool, the ‘wheelbarrow’ odometers and the Aristotelian solar system model rested on the analog principle, that is, they were an imitation of the represented system, but smaller. The term ‘analog’ means alike: there is a physical resemblance between the two systems and the sole difference is found in their scale. In the analog device the data are physical and continuous, while in the digital devices the data are discreet data, numbers or symbols.

There is a common misapprehension and ambiguity as to classification between analog or digital tools utilizing cogwheel gear mechanisms of any type. The distinction is obvious when we realize that the digital tools function on discontinuity, or discrete intervals. In the cogwheel gear mechanism, the teeth of the wheels create these discrete intervals that could be counted. Hence, any toothed cog or gear mechanism is considered a digital mechanism (including the common spring timepiece) when it divides continuous movement into even discrete intervals measurable as discrete units of any kind, translated as time or as distance. On the other hand, if the cogwheel gear mechanism applies smooth wheels (without any type of teeth), it is evidently continuous, to be classified as analog. It is yet more complicated when we have a hybrid of both, combining smooth wheels with toothed gears as in the odometer. In this case we have an analog—continuous—input of data by the smooth wheel which has constant contact with the earth while moving on it, but then the data from that smooth wheel are fed into a gear, dividing the continuous movement into distinct intervals and counts, digitally translating them into Roman miles.

From the Roman era up to the introduction of the mechanical clock during the 12th and 13th centuries, toothed cogwheel gear mechanisms were employed for the transmission of energy from water wheels. It was the mechanical clock that gave renewed acceleration and dimensions to the cogwheel gear mechanism. The rapid development and abundance of monasteries at the end of the 12th century promoted an interest in creating ordered time allocations, hence the appearance and diffusion of the mechanical clock. In the mechanical clock the focus was on developing an accurate mechanism which would break down the continuous movement created by the energy of weights, the pendulum, or by the spring, into even and discrete constant pauses, intervals or actions that could be measured, counted and translated into basic time units. Like odometers, these clocks fed analog input into a digital apparatus. With these types of distinct and discrete intervals, various kinds of manipulations became possible. The first clocks were not intended to show a precise time; they were intended to announce and regulate a definite order of life according to which a community of monks and those affiliated and surrounding it would have to act and behave. Therefore, in the initial stages facilities developed, and various sounds of bells announced the event due to take place. For instance, morning or evening prayer, or starting or finishing work. The English word 'clock' derives from the French word *'clocher'*, which means the turret or tower of a church, monastery or cathedral where the bell or clarions are located, or sometimes the bell itself [8].

John Napier's (1550-1617) Bones/Rods

Until the introduction of the Napier logarithms (1614), there was no noteworthy development in calculating instruments. The abacus was the most commonly accepted calculating facility, other than dactylology, the technique of calculating with the fingers on one's hands. The decimal base representation gradually turned out to be the preferable mathematical number and quantity representation system of the Western World. In a small pamphlet written by Napier in 1617, titled 'Rabdologia', there is evidence that he developed several auxiliary tools to carry out multiplication. The origin of the word 'Rabdologia' is uncertain and in dispute. In ancient Greek it is a bundle or collection of sticks, derived possibly from *'rabdos'*, 'stick' and *'logia'*, 'collection'. It is also possible that Napier borrowed the name from Stephanie's book *Glossaria* (1573). According to another opinion found in William Leyboum's *The Art of Numbering by Speaking Rods: Vulgarly Termed Napier's Bones* (1667) [9], the meaning of the word 'Rabdologia' is 'speaking rods', once again derived from *'rabdos'*, 'stick' and *'logos'*, 'speaking'. He writes,

> 'The difficulty and proximity of calculation, the weariness of which is so apt to deter from the study of mathematics, I have always, with what little powers and little genius I possess, labored to eradicate. And with that view, I have published of late years the canon of logarithms … for the sake of those who prefer to work with the natural numbers as they stand, I have excogitated three other compendious modes of calculation, of which the first is by numbering rods and these I called 'Rabdologia'. Another, by far the most expeditious of all for multiplication, and which on that account I have not ineptly called the promptuary multiplication, is by means of little plates of metal disposed in a box. And lastly, a third method, namely local arithmetic performed upon a chessboard.' [10].

The second facility mentioned by Napier is based on a few rods, plates of metal or wood, nicknamed 'Napier's bones', because some were made of ivory or other animal bones. Along each of these rods whole numbers were imprinted according to a preset order, representing columns of numbers of a multiplication table. According to a certain procedure, the rods were arranged for multiplication, the division of two numbers or the extraction of a square root.

It appears that the Napier's rods derived from a commonly accepted multiplication procedure, which is still common. This procedure was, evidently, introduced by the Indians and was brought to Italy in around the 14th century. There is also evidence that it was used by the Chinese and the Persians in the Middle Ages. In Italy it was called 'Gelosia', meaning a grid. Let us try to trace the possible routes of the development of Napier's rods.

1) Today's method of the multiplication of two numbers may follow the following procedure:

```
4185
x752
——
8370
20925
29295
————
3147120
```

2) The Gelosia procedure is much the same:

```
 4185
 x752
 ——
 8370
 20925
 29295
 —————
```

The addition is performed diagonally because 3147120, the numbers deduced from the multiplication, are set directly one beneath the other. To prevent errors, diagonal lines were marked to follow the desired pattern of the order of additions, thus appearing as follows:

```
4185
 x752
 —————-
 \8\3\7\0\
 2\0\9\2\5\ \
- 2\9\2\9\5\ \ \
 \-\-\-\-\-\-\-\
 3 1 4 7 1 2 0
```

As an example let us see how rod numbers 7 and 2 are imprinted to serve as columns of a multiplication table for numbers from 0 to 9 inclusive:

rod number

7	2
7x0= 0/0	0/0=2x0
7x1= 0/7	0/2=2x1
7x2= 1/4	0/4=2x2
7x3= 2/1	0/6=2x3
7x4= 2/8	0/8=2x4
7x5= 3/5	1/0=2x5
7x6= 4/2	1/2=2x6
7x7= 4/9	1/4=2x7
7x8= 5/6	1/6=2x7
7x9= 6/3	1/8=2x8

The other rods from 0 to 9 follow the same principle. Now, when we want to multiply the abovementioned two numbers (4185x752) we have to arrange the rods so that on their upper part the numbers 4;1;8;5 will appear, and then put against them the only rod bearing number from 0 to 9 which serves as the multiplier. Each time we deduce a result for one digit; we can start at the rightmost or at the leftmost digit and from there proceed systematically in the opposite direction. In our case we will start with the number 2 followed by 5 and 7. We add diagonally the numbers that are in line two (parallel to number 2 of the multiplication rod).

Example of multiplying 4185x752:

The upper values of the rods forming the number 4185 are set against the digit 2 of the multiplying rod of number 752 are.

Rods	forming the number 4185			multiplying rod:
4	1	8	5	(1)
0/8	0/2	1/6	1/0	(2)
				(3)
				:
3/2	1/4	5/6	3/5	(7)
				:
				(9)

Note that, in the line formed against number (2) under the rod bearing the digit 4 at its top, there is only one number which has the value of 8 and an empty place demarcated by the zero digit. We start to add from left to right:

the 8 on rod 4 is to be added to the 0 on rod 1, and the result is 8+0=8; the 2 on the rod with 1 on its top is added to the 1 on the rod with 8 on its top, which gives 2+1=3; the 6 on rod 8 is added to the 1 on rod 5, which is 6+1=7; and finally there remains only the zero digit on rod 5. We get the final result by writing down the deduced additions. Hence, the multiplication result is 8 3 7 0, coinciding with the result of the multiplication 4185x2=8370. We can proceed in the same manner with 5 and 7 to get the total result (this example can be found in E. M. Horsburgh, *Calculating Machines* (1920), pp. 6-9) [11].

The development of Napier's bones serves as an example of a transition from an 'abstract' mechanical calculating procedure to a mechanical concrete device. Mechanical calculating tools doing calculations in a fixed and rigid pattern without the need to find out new ways of reckoning each time. If we possess this ability of having a fixed pattern, procedure or algorithm, the passage to the construction of a machine is possible though not necessary. The case of Napier's rods is of this trend materialized.

At the outset the rods were flat. As there was a need for several copies of the same rod to represent a large number, a considerable number of rods were needed. It only took a short time to introduce square rods, enabling four colunms of imprinted numbers and resulting in a considerable reduction in the number of rods. The most advanced version was the cylindrical rods, enabling the inscription of ten columns on each of the rods, thus minimizing the number of rods. The advantage of the cylindrical rods, in addition to their larger capacity of storing data, is that they could be set up in a frame and serve as a very convenient tool to obtain multiplication results quickly and directly. With specially inscribed rods, it was also possible to perform square roots operations or the raising of powers.

The cylindrical rods were utilized in many mechanical calculating devices to carry out direct multiplications. For now, direct multiplication will be defined as obtaining a result *via* a single action, and not by any reiteration or repetition method mechanism. The first to adopt the cylindrical Napier rods in a mechanical calculating machine was Wilhelm Schickard (1592-1635) of Tübingen University. In two letters, written on 20th September 1623 and 25th February 1624, Schickard informed Kepler about a calculating device that he had developed capable of performing the calculation operations of addition, subtraction, multiplication and division. The device he mentioned, probably the second model, was destined for Kepler; having been handed over for manufacturing to a local craftsman, however, it was destroyed in a fire. Professor Baron von Freytag Löringhoff found the original drawings in the state library of Stuttgart in 1957. Using these, he reconstructed a working model of the Schickard machine. A copy of it is displayed at the Deutsches Museum in Munich [12]. The machine comprises two separate parts functioning on two different principles, physically set together. The upper part of the machine, founded on the cylindrical Napier rods, is designed to carry out multiplication operations, while the lower part of the machine, based on the toothed cogwheel gear mechanism, is designed for carrying out addition and subtraction operations, from data set with a nib. The original drawing sent by Schickard to Kepler was found recently at the Pulkovo Observatory Library near St Petersburg in a copy of the Rudolphine tables prepared by Kepler, forgotten for all these years and serving merely as a bookmark.

Samuel Morland (1625-1695) used the Napier bones principle in a calculating device he developed to perform multiplication, division and extraction of square roots. Morland engraved the Napier rod numbers on small flat disks, so that the digits could be displayed immediately beneath a display window on the upper part of the device. His book, *The Description and use of two Arithmetic Instruments* (1672), offers a description of that device, as well as an account of an adding machine, based on a toothed cogwheel gear mechanism, in which the data were set up with a nib, intended to carry out adding calculations in English currency.

Gaspar Schott (1608-1666), a German Jesuit mathematician, described more or less at the same time methods of mechanical calculations that a gentleman with technical awareness was required to possess in the 17th century. Schott included in his work not only the calculating procedures, but also the mechanical auxiliary tools that had been developed by his day. One of these instruments, the *Organum Mathematicum*, was a considerable extension of the application of Napier's bones. This instrument enabled the performance of addition and subtraction operations to solve geometrical problems, mainly concerning land surveys, and to calculate the strength of fortifications. It was also capable of assisting a wide assortment of calculations, including arithmetic, cryptography, and music. It also contained tables to calculate and determine the following: calendar dates of Christian holidays; the direction, length and declination of sun dials; sun movement orbits; and the time of sunrise and sunset on any given day of the year. The instrument contained tables to calculate the movement of the planets and the preparation of horoscopes as well. It also had two types of tables to calculate quantities in construction, digging and covering trenches. It had a special set of Napier bones to harmonize music and melodies. Unaware of Schickard's work, Schott linked cylindrical Napier bones to a frame and constructed a calculating device that was a failure, as it was too confusing and fraught with errors in operation. In other places we also find the construction of devices that applied the cylindrical Napier rods in a similar manner to Schickard and Schott. In France, Pierre Petit (1594-1677), a close friend of Pascal, worked on it. These undertakings to apply the Napier rods in a calculating device failed for the very same reasons as Schott's device failed: inconvenience and errors in operation. After a while the Frenchman René Grillet de Roven (1678) tried to combine cylindrical Napier bones with a toothed cogwheel mechanism [13]. The English leading scientist Robert Hooke (1635-1703) constructed in 1673 an abortive model of a calculating device based on Napier's bones. It was an unsuccessful imitation of Morland's device.

In the 19th century, interest was revived in the Napier bones as a direct multiplication component for calculating machines. In the USA, Barbour (1872) and Vera Ramon (patented in 1878) attempted to incorporate the Napier bones principal mechanically, but with no practical success.

We proceed now to the development of digital calculating tools based on cogwheel gear mechanisms.

Digital Mechanical Calculating Tools

Fundamental principles of operation

In digital calculation, the basic operation is counting, whence derives all other arithmetical calculating operations such as addition, subtraction, multiplication and division. The counting operation can be defined as an adding operation in which each time an equal number is appended to the previous number. It can also be considered as an iteration loop procedure in which we constantly add a given fixed difference to the last sum. Commonly in counting, this given fixed difference addition is that of a single or discrete unit of one. Hence, other arithmetical operations can be derived from it. Subtraction is the reverse of counting, in which we deduct an equal amount of units each time. Multiplication is nothing else than a repeated or iterative addition of the number to be multiplied. In other words, a counting with intervals larger than one numerical value unit. Counting by the difference of two (2; 4; 6 ... 2n) performs multiplication by two, while counting at intervals of five provides multiplication by five, etc. The same relates to division. By counting the number of the repeated subtractions of the constant interval of the divider, the result is deduced. For example: 100 divided by 25. Let us subtract the divider 25 from 100: we get 75, the counter is now on 1; if we do it iteratively, then 75-25=50, the counter is on 2; 50-25=25, the counter is on 3; and finally 25-25=0, and the counter is set on 4. Thus, the deduced result of 100 divided by 25 is given on the counter as 4. Naturally, when a remnant is left which is smaller than the divider it is added to the last number set on the counter.

We may now conclude that the mechanical counting operation involves two very distinct procedures: (i) the summation of the numerical values; and (ii) the passage of the carry, which requires the transfer of the numerical value of a digit from one place or location in the number to another. In order to perform the summation action there are five mechanisms based on the wheel:

1. A wheel with equal teeth.

2. A wheel with changeable teeth.

3. A wheel with stepped teeth.

4. A wheel with segmental teeth (having a certain toothed sector on only part of the whole wheel).

5. A wheel with a dual set of teeth (internal and external).

As for the carry transfer action, a ratchet-driven gear mechanism is needed to indicate each time when an entire rotation of the counting wheel has occurred and causes its left neighboring wheel always to rotate only by one tooth, thus increasing its numerical value number by an increment of one.

Mechanisms like those incorporating cogwheel gears were already known in ancient Egypt, Greece and Rome [14]. In the Middle Ages, and even earlier, toothed cogwheel gear mechanisms were integrated to transfer water energy from water wheels. In the 12th century toothed cogwheel gear mechanisms were incorporated into mechanical clocks and automata as devices intended to imitate artificially human or animal activities.

Calculating Machines (1623-1900)

Until 1935 the most common auxiliary tools for digital calculation were the office mechanical calculating machines. These were activated manually by hand or by mechanical tools such as a lever or crank. The electric driven motor was introduced into such machines not before May 1901. In the 1920s the term 'office automatic calculating machines' referred to machines in which the multiplication or division operations were performed by a single stroke. That could be achieved with a special mechanism based on multiplication-division tables or repetitive adding-subtracting operations by the machine itself without the intervention of a human operator. In most office mechanical calculating machines, the calculations were carried out by means of a calculating component based on the toothed cogwheel gear mechanism which originated in the calculating instruments of Schickard (1623), Pascal (1642) and Leibniz (1673).

The computations carried out in all the digital calculating instruments rest on a calculating component applying the principle of subsequent counting, one after the other, of like objects organized in constant differences or intervals, enabling the representation of series of numbers. To repeat, the counting operation is a fundamental arithmetical operation of repeated addition or subtraction at a fixed predetermined interval. With regard to the computing component, that of a digital calculating tool, the counting of entities is performed by the teeth on a cog or gear, or otherwise the protrusions or spokes found on the outer circumference of a turning wheel. As the number of the teeth on the gear is constant and the procedure of the mechanism is iterated and successive, the counting on the wheel's circumference is continuous and successive, so that every move by a single tooth of the gear increases or decreases the counting by the order of one unit. The numerical representation of that unit may also serve as its numerical base representation, selected by the designer of the counter. In a decimal, digital calculating tool comprising a cogwheel gear mechanism, the number of digits, and hence the range of the number, is determined by the number of counting wheels. A mechanism with four counting wheels can represent numbers no larger than 9999. Each counting wheel has ten teeth, so every passage over a single tooth increases or decreases the number by an increment of one. Since the order and the number of counting wheels and its geared teeth are fixed, the rightmost counting wheel serves to represent the unit digits of the numerical position representation, the next wheel to its left represents the tens, and so on to the hundreds and thousands.

To perform an addition operation, we must first set up one of the numbers on the counting wheels. Then we add the second number by rotating the gear's teeth to a new position, thus causing a new reading of numbers due to the cumulative rotation of the gears. The passage to a multiplication or subtraction operation is simple, obtained just by repeated adding or subtracting operations. For example, if we want to multiply 4x2, first we set the number 4 on the units counting wheel by rotating it by four teeth, so that the digit 4 appears on the display window; next we move the same wheel by four more teeth and the digit 8 will snap into place, indicating the result of 8 on the display window.

Hence, the number of counting wheels limits the size of the number that can be represented. In the decimal, digital calculating instruments, each of the counting wheels has ten teeth to represent the ten digits from 0 to 9 inclusive. In these devices the number representation is the local numerical position representation. The function of the cogwheel gear mechanism is thus to imitate mechanically the numerical position representation to carry out the counting operation and perform the carry transfer from one wheel to the next to its left after the completion of a whole rotation of the wheel.

Mechanical Calculating Tools

The first application of the toothed cogwheel gear mechanism for calculations was accomplished by Wilhelm Schickard (1592-1635), Professor at Tübingen University, for the purposes of mathematics, astronomy and Hebrew. In two letters to Kepler (20th September 1923 and 25th February 1624), he describes his machine as follows:

> 'Which numerical data are stated by automatic calculation, adding, subtracting, multiplying, and division. Shows clearly how accumulates and transfers itself the carry of tens and hundreds to right when increasing or deducting something' [15].

This machine was reconstructed in 1957 by Professor Baron von Freytag of Tübingen University with the help of Erwin Apple, an expert in fine mechanics.

The next step in the development of digital, mechanical calculating instruments was accomplished by Blaise Pascal (1623-1662). Pascal was borne just when Schickard designed his machine. Between the years 1642 and 1644 Pascal designed and constructed a small and simple calculating machine. This machine design was inferior to Schickard's machine and its scope of operation was limited to addition and subtraction [16]. Pascal's machine was designed solely to assist his father, a tax collector, to carry out calculations in French money, which at that time had a numerical base of 12. The machine was founded on horizontally toothed gears placed one next to the other, enabling an automatic transfer of the carry. The data on the horizontal wheels were set by a nib. Pascal tried to promote wholesale production and marketing, but the high price per unit, equivalent to the wages of several human computers, caused the project to fail. It seems that

Pascal built some fifty machines of this type, but he could not find buyers for them. To promote the sale of the machine, Pascal gave one of the first prototypes to Queen Christina of Sweden in 1652. At present, we know of eight of Pascal's machines which were preserved. Of these, four are found in Paris at the *Musée des Arts et Métiers* (the Technological Museum of Paris).

Gottfried Wilhelm von Leibniz (1646-1716) was the next person to mark a milestone in the development of calculating tools. Leibniz learnt about Pascal's work and we may assume that he even saw one of Pascal's machine models during his stay in Paris from 1662 to 1676. But we do not know if Leibniz was aware of Schickard's machine. In 1671, Leibniz conceived a device to perform all of the different arithmetical calculations. After a long time and many upheavals, the construction of the first working prototype ended in around 1694. Many histories of mathematics report that in 1673 Leibniz introduced his calculating machine to the Royal Society of London that elected him as a Fellow. I shall return to this later.

What made Leibniz unique as a developer of calculating tools before Babbage (1781-1871) was on the one hand his approach to the design and construction of the instrument, and on the other hand his approach to calculations. For Leibniz, calculations were a dull necessity and a waste of time to relegate to slaves. For him, the idea to mechanize computations was a part of a more general comprehensive concept in which the whole process of reasoning was to be mechanized. He was looking for a method according to which reasoning would be restricted to a certain sort of reckoning, enabling decisive answers for any dispute by means of a machine. Leibniz was also one of the first to grasp the practical advantages of the binary base representation for applications in mechanical calculations [17].

Francis Bacon (1550-1626) had already proposed the use of a binary code comprising a 'five-bit register', an equal and fixed series of characters of two symbols, for diplomatic mail. In his book *De Augmentis Scientiarum* (1623), a description of that code is presented for the 24 letters of the alphabet as in use at that time. The code rested on two symbols—a and b—and represented letters in the following manner: the letter a was represented as aaaaa; aaaab stood for the letter b; the letter c was represented by aaabb, etc. Apparently, this was the first time that the binary base representation (and a fixed five-bit register) was proposed in detail and was clearly for practical use. Naturally, the symbols a and b can easily be replaced by a 1 (one) and a 0 (zero) [18].

In 1672, Leibniz designed a transmission gear component, known as the Leibniz wheel or the Leibniz stepped reckoner, which was no more than an improvement of the regular toothed wheel. Even if Leibniz had learned about Pascal's calculating machine during his stay in Paris (1672), his machine differed from Pascal's on two counts: the presentation of the data for calculation and the transfer gear component. The Leibniz transfer gear comprised a wide cylinder that, on its external circumference protruded ten stepped teeth varying gradually in their lengths, one shorter than the other by a definite size, leaving beyond each tooth a smooth plane on the cylinder. Due to this unique structure it was named the 'stepped reckoner'. Each length of a tooth represented one of the ten numerical decimal digits. Setting a given number caused the wheel to rotate up to there and not beyond, as beyond these teeth the circumference face of the cylinder was smooth and toothless, while the motivating wheel would move free without causing any movement of the stepped wheel. This is one of the first control mechanisms in calculating tools in which the avoidance of errors was imprinted in the hardware. This improvement, achieved by Leibniz, enabled automatic counting and halting of the operating handle by the machine itself, thus bringing to an end the human errors caused during multiplying or division operations when applying the repeated adding or subtracting method in digital, mechanical calculating machines. Hence, in Leibniz's machine the multiplying and division operations were performed 'automatically' by repeated adding and subtraction.

A prototype of Leibniz's machine was presented before the Royal Society in 1673. There Leibniz met Samuel Morland (1625-1695), who in 1666 developed a machine similar but inferior to Pascal's machine, intended for performing adding calculations of English coins. Morland's adding machine had no automatic carry transfer and the operator had to do it manually by moving the carry digit on a separate counter. Morland tried to raise interest in the machine by advertising it in the *London Gazette* of April 16, 1668. Morland, a prolific inventor in other fields as well, succeeded in developing a method for cracking seals. He stayed for some time in Sweden (from 1653) and we may assume that he might have seen Pascal's machine presented to Queen Christina.

Robert Hooke (1635-1703), secretary of the Royal Society, expressed disdain for Leibniz's and Morland's machines, writing in his diary: 'Saw Sir S. Morland's arithmetic engine, Very silly'. Hooke committed himself to constructing a prototype of a more promising calculating device, based on Napier's bones. Hooke demonstrated such a prototype before the Royal Society on March 15, 1673 (although this date needs to be readjusted as there then occurred the change to a new calendar). A few weeks later, on May 7, he presented, on the demand of Fellows of the Society, a more detailed description of the device. Despite the great resemblance of Hooke's device to Morland's device, it could not compete with the machine designed by Leibniz later on. Morland meanwhile designed a second calculating device, which was only introduced in 1673. It automatically performed multiplying operations, but by means of a mechanism founded on Napier's bones set up manually. However, due to Leibniz's continuous desire to improve his device design, it caused him a great delay in its presentation before the Royal Society. Leibniz could not fulfill his commitment, as promised to the Royal Society, and this damaged his prestige and later ruined his relations with the Society [19].

Leibniz's first working model was only completed by 1674. It was a far more advanced model than anything constructed earlier. Only at the end of October 1676, before his return to Hanover, did Leibniz stop for a few days in London and demonstrate the functioning of his machine [20]. It seems that in 1694 he constructed his last model of a calculating machine, which is still preserved at the Hanover State Library, Germany. After that, Leibniz abandoned his interest in developing calculating devices.

In Europe during the 18th century, several designs and constructions were made of digital, mechanical calculating devices based on toothed cogwheel gear mechanisms. The difficulty in building such devices derived, in my judgment, from a shortage of craftsmen ready to devote themselves to this sort of work. Clockmakers were suitable craftsmen for constructing these types of devices and measuring instruments. It is known that a few Jewish craftsmen were involved in the development of this type of calculating device. For instance, the clockmaker Yana Yakobson of Nieswiez, a small town in the province of Minsk in Belarus, constructed no later than 1770 a 'machine for mechanical calculations', as is imprinted on it in Polish (*'Machina Mechaniszna do Rachunku'*) and in German (*'Mechanische Rechnungs Maschine'*). The machine could perform the four basic arithmetical operations [21]. The Polish Jewish scholar Abraham Stern (1769-1843) designed and built a series of calculating devices that carried out the four basic arithmetic operations and the extraction of square roots up to the order of the sixth digit. He exhibited the most advanced model of his device during a public lecture given in Warsaw on April 30, 1817 [22].

Of the additional and more famous developments of digital, mechanical calculating devices, based on toothed cogwheel mechanisms, a few deserve to be mentioned. One was designed by Giovanni Poleni (1683-1761), an

Italian professor of astronomy at Padua. In 1709 he tried to design a device very similar to that of Leibniz. In Germany, Jacob Leupold (1674-1727) and Philipp Hahn (1739-1790) each independently constructed in 1770 a similar calculating device. In England in 1775, Charles Stanhope, Earl of Stanhope (1753-1816) also constructed a matching device. We learn of these and more devices from the personal records of the developers on their calculating devices and from literature from that period. An example is the writings of Christian Ludwig Gersten (1701-1762), professor of mathematics at Giessen, of 1735 [23].

By the turn of the 19th century it was possible to construct a digital, mechanical calculating device that rested on a toothed cogwheel gear mechanism and that was reliable enough for practical use and mass production. This was the ‘Arithmometer’, a device built in 1820 by the Alsatian Charles Xavier Thomas (1785-1870) from the town of Kolmar. This, known as the Thomas machine, was produced by different firms under various names with minor modifications until the end of the 19th century. Until 1865, five hundred such machines were produced, and in the proceeding thirteen years a further thousand machines were made [24].

In 1875 the American Frank Stefan Baldwin (1838-1925) obtained a patent to improve Leibniz’s ‘stepped reckoner’ following the invention of the pinwheel calculator in 1874. He started the design of a new machine in 1905 and was able to finalize its design with the help of Jay R. Monroe, who eventually bought the exclusive rights to the machine and started the Monroe Calculating Machine Company to manufacture it. On the surface of a toothless cylinder, ten holes were arranged through which ten bolts could protrude, to represent digits from 0 to 9. Almost at the same time, the Swede Willgodt Theophil Odhner (1845-1905) designed a machine that operated according to a similar principle. In Germany, between 1892 and 1912, the firm Brunsviga manufactured twenty thousand such machines of this model alone [25]. The multiplying operation in this machine was performed by iterative adding. The improved version of the ‘stepped reckoner’ enabled considerable reductions in the size and bulk of the machine. Many calculating machines were manufactured under Odhner’s patent by different firms under various names: in France, Rapid (1892), Marchant (1911), and Monopol-Duplex (1894); in England, Colt (1912), Britannic 1 (1922), and Gauss (1923); in Germany, Dactyle (1905), and Sanders (1912); in the USA, Facit (1918); and in Sweden, Demos (1923). Most of these machines could represent eight-digit numbers.

In 1927 a new model was introduced by Bronsviga, the *Bronsviga Nova*, which included one register to store intermediate results, enabling direct retrieval and setting-up of data from the register to the calculating mechanism. In a preceding model, the *Bronsviga Triplex*, it was only possible to store the final result in the register, yet of a number of up to twenty digits. The Triplex enabled the number in the register to be divided by two, and to perform a multiplication operation of two different numbers by a multiplier.

The first known patents for calculating devices performing direct multiplication were issued in the USA to Edmund D. Barbour (1841-1925) from Boston in 1872 and to Ramon Vera from New York in 1878. In France Léon Bollée (1870-1913) designed and built a direct multiplying machine in 1889, based on a series of protruding bolts which was a metallic reconstruction of the multiplication table up to the number 9 [26]. He needed it to help prepare extensive tables of bell dimensions. In Germany Otto Steiger (1858-1923), a Swiss engineer who lived in Munich, in 1892 received his first patent for a calculating machine of direct multiplication; his 'Millionaire' calculating machine of 1893 had a one stroke direct multiplying mechanism, also based on the multiplying table. Within three years, Steiger had produced and sold more than one thousand machines of this model. From 1915, this machine was manufactured by Hans W. Egli (1862-1925), a Zurich-based manufacturer. In total, between 1894 and 1935, some 4600 machines of this brand were sold [27].

In contrast to the direct multiplying mechanism, the installation of the direct dividing mechanism in calculating machines began not before 1912 in a machine of the American manufacturer Jay Randolph Monroe (1883-1937), based on a machine designed by Frank Stephen Baldwin (1838-1925). Known as Monroe Systems for Business, his company was also known as the Monroe Calculating Machine Company, Monroe THE Calculator Company, and Monroe Division of Litton Industries. However, until the 1940s most of the calculating machines' manufacturers continued to adopt the principle of repeated adding and subtracting for multiplying and dividing [28]. In 1932 an electrical direct multiplying mechanism was incorporated in calculating machines. It was based on the multiplication table principle. The firm 'The International Multiplier' produced multiplying equipment based on punch cards (on this issue see more in the section about punch equipment) [29].

The output of results printed on paper was only incorporated and introduced in calculating machines in 1920, though a patent for it had already been issued in the USA in 1876.

At the turn of the century, many digital, mechanical and electrically driven office calculating devices were constructed around the world. So far I have mentioned some of the calculating tools that are considered milestones and meaningful improvements upon their predecessors as well as commercial successes. In the coming sections I will concentrate on additional improvements made to this type of machine [30].

Key Set-up and Driven Calculating Machines

Calculating machines set up, driven and operated by means of keys or push buttons are in essence an American development. These machines are divided into two distinct groups: those in which the data are set up by keys and those driven by function keys. This means that the energy for their operation is invested through pressing a key, which also functions as a lever, without the need for any additional auxiliary action, such as pulling a lever in order to produce the result in the display window.

In 1887, the American Dorr Eugene Felt was awarded a patent for the ‘Comptometer’, a calculating device driven by keys. Even before 1887, many devices operated by keys had been developed. For example, in 1850, in the USA the first patent for a key-driven adding machine was issued to D. D. Parmalee, enabling the addition of a single column of digits at a time. Later on, a similar device was also developed in Germany, the ‘Torpedo’, in England, the ‘Plus’, and in the Switzerland, the ‘Direct II’.

A key set-up calculating machine, driven by means of an electric motor and equipped with a separate key for multiplying and with an automatic carry, was designed in Boston by Emory Seymour Ensign (1879-1944) in 1905. To repeat, there is no recording of an electric motor-driven calculating machine prior to 9th May 1901.

Automatic Calculating Machines

As the meaning of the term ‘automatic’ as attributed to calculating machines has varied over time, I will use here the definitions linked to this term that prevailed until 1935, as they appeared in various advertisements. An automatic machine was then considered until the 1950s as a machine that had a single stroke multiplying or dividing mechanism and that was driven by a mechanical or electric motor. In 1920, the first such totally automatic digital calculating machine appeared on the market, designed by Frank S. Baldwin (1838-1925) and Jay R. Monroe (1883-1937). It still applied the toothed cogwheel gear mechanism as its basic calculating component, yet it was electro-mechanical, electric motor-driven. In contrast, the first known commercial electric-motor driven machine was the 'Marchant' of 1911, designed according to the 'Odhner' model.

Twin Calculating Machines

The twin machines were made of two identical calculating machines joined together by one operating system mechanism. This type of calculating machine was intended to provide parallel calculating operations of two identical computing procedures or algorithms, while the data set in each of the twin machines normally differed. These were used for deducing grid references consisting of two numbers representing the x and y coordinates, respectively, in mapping (cartography), survey, geodesy or artillery. The data were set up separately on each of the twin machines, and the performance of the calculations was done by rotating but a single operating handle, causing a parallel and simultaneous deduction and output of the results by both machines. The German calculating machine firm Brunsviga had already developed such a model by 1927, followed by the American firm Marchant.

Cash Registers

Cash registers were introduced during the second half of the 19th century, and were intended to solve problems of cheating in shops and in business. In due course, they turned out to comprise an automatic tool for the recording of sales transactions and for issuing receipts for customers. Hence, they are 'data systems' with several components. The cash registers were accepted as a very useful auxiliary in management, enabling the immediate and comprehensive concentration of all data and information on the shop. These devices incorporated the decimal, digital, toothed cogwheel gear mechanism as a calculating component, usually just as an adding element. The American firm National Cash Register (NCR), the pioneers in this field, was founded in 1884 and produced more than a million cash registers of various models until 1947. Its most successful model was the National 27 that enabled an output of intermediate balance to be obtained in real time, according to the selling state in a given department within the shop, or an accumulation of the total balance in any of the departments and a final balance output of all sales carried out in the shop. The National 27 was subsequently adopted for bookkeeping and accountancy.

Since 1919, cash registers have been designed with automatically opening money drawers. They also performed after each transaction management and control of income balance functions. A more advanced model of cash registers that were abundant until 1935, were those introduced in shops and businesses that did adding and subtracting operations, and sometimes also multiplication and division, enabling the comprehensive management and control of all transactions of income. In addition to the calculating component found in the digital office mechanical calculating machines, storage means, known by the name ‘register’, were installed in cash registers. They served then as intermediate storing auxiliaries; their data were diverted for storage to sum intermediate calculation results. In the most sophisticated cash registers there were up to six such storage registers, enabling the storage of numbers of eight to twelve digits.

Certain cash registers and digital calculating machines had also integrated output components to obtain printed copies of intermediate or final results on rolls of paper. The traditional printed output on a paper tape was introduced in the cash register as early as in 1874.

Editing and Recording Machines

Editing and recording machines were designed to produce a printed output of numerical data or information arranged in the desired format. These machines were introduced, mainly in the USA, in the last quarter of the 19th century. The idea of printed output from calculating devices had already originated earlier with Müller (1746-1830) in 1783 and with Babbage (1791-1871) in 1834. He incorporated a printing mechanism in his difference engines (see following section). In 1851 the Swedes George and Edvard Scheutz also succeeded in constructing a difference engine with a printing mechanism. However, the integration of paper tape in a calculating machine’s printing output mechanism for cash registers was only tried out for the first time in 1872—by the American E. D. Barbour. He managed it by linking to an adding machine a tool for printing, such as a typewriter. Similar designs were also produced by the American Frank Stephen Baldwin in 1875, the Frenchman Henri Pottin in 1883 and A. C. Ludlum in 1888. Yet the first practical editing and recording devices were constructed independently by the Americans Dorr E. Felt (1862-1930) in 1889 and William S. Burroughs (1857-1898) in 1892. Though the printed output on paper tape was introduced in the cash register by 1874, it was not introduced in office digital calculating machines before the 1920s [31].

Editing and recording machines turned out to be very popular, because they enabled convenient control of the calculation of results. Of these machines, many models were designed and produced in vast quantities. The Burroughs firm alone designed more than one hundred models and produced over a million such machines before 1947 [31]. The editing and recording machines can be classified as follows:

1. Machines that have one counter, with or without a mechanism for direct adding.
2. Duplex machines and machines with a large number of counters, with or without direct adding. The existence of two or more separate counters enabled the performance of several operations in parallel. On the other hand, in machines with a single counter the operations were performed sequentially and gradually.
3. Machines that extract invoices and for accountancy. These machines were intended to provide receipts, invoices, reports, forms, orders and documents for business management. Some of these machines incorporated a calculating component linked with printing element or a typewriter. The first machine of this kind was designed by Hubert Hopkins. Hubert's or Bollée's machines or the Millionaire calculating machine, had incorporated a direct multiplying component. These machines achieved very high standards of performance with quite complex and prolonged calculations carried out automatically.

There were editing and recording machines in which the operations of adding, printing, recording, sorting, etc., were carried out by pressing special keys. In other models those operations were controlled by sophisticated programming, carried out by a moving printing cradle similar to that of a typewriter. Certain models had an additional keyboard, thus enabling the setting of a second series of data while the previous dataset was still in a processing or calculating state. In these machines the driving power was mechanical or electrical. The most abundant type of keyboard was the one in which every digit had a predetermined key. This was named a full keyboard. In some machines there existed only one set of ten keys, which set up the various functions automatically, one after the other, for example in Dalton's machine of 1902 and Sunstandart's of 1914. In machines that had a 'Repeat' key and ten number keys it was possible to perform the multiplying operation by iteration.

This type of machine was brought from the USA to Germany in 1916, where extensive design improvements were made. During the 1920s, typewriters to which an adding component was incorporated existed; for example, in Germany, the Urania-Vega model of 1920 and the Mercedes-Electra model of 1924. Later Zuse integrated this model into his Z3 computer of 1943. In parallel, there were various experiments for synthesizing and synchronizing calculating machines with standard typewriters, electric typewriters in particular, such as those of the Spanish inventor Leonardo Torres y Quevedo in 1920.

The adding component was also integrated into other commercial applications, such as the Addressograph, an automatic machine used to imprint post charges on outgoing corporate mail and to accumulate the total debited sum of money [32].

The Difference Engine

The difference engines were originally designed to produce mathematical and astronomical tables, in order to prevent uncontrolled errors and inaccuracies. Between 1783 and 1909 several calculating machines were designed and built, in which Newton's mathematics based on the differences principle was adapted. In these machines, named after Babbage's famous difference engines, the toothed cogwheel gear mechanism was also utilized as the principal and sometimes the sole component for the calculating and storing of data. The application of the difference principle was intended to prevent accumulative errors that dragged through the calculations. The difference method specifically fits the multiplication operation or the solution of algebraic polynomial equations. This method enables the performance of calculations by approximation by means of polynomials. It was introduced by Brook Taylor (1685-1731) in his 1715 book *Methodus Incrementorum* and by Colin Maclaurin (1698-1746) in his 1742 book *Treatise of Fluxions*.

Until the introduction of the difference engine concept in 1786, the common technique by which the digital, mechanical calculating devices performed the multiplication operation rested on repeated addition or Napier rods.

> 'The method of differences, although once the main tool of all table makers, has, of late, fell into disfavour. Thus a few words about the method itself might well be in order for the majority of readers. If a function, such as $F(x) = 2x + 3$, is evaluated for successive values of x, and then the difference noted between each adjacent value of F(x), one finds:

x =	1	2	3	4	5	6	7	8	9
F(x) =	5	7	9	11	13	15	17	19	21
differences =	2	2	2	2	2	2	2	2	

> If the function was F(x) = x2 + 2x + 3 then it would have been necessary to obtain the differences of the differences (or second differences) before a constant difference was obtained.
>
> For example:

x =	1	2	3	4	5	6	7	8	9
F(x) =	6	11	18	27	38	51	66	83	102
first difference =	5	7	9	11	13	15	17	19	
second difference =	2	2	2	2	2	2	2		

> In general, if the polynomial to be evaluated has a term of x" in it, then it will require the nth difference to be taken before a constant is obtained. If one has to evaluate a polynomial for many values of x (such as when computing tables) it is easier to do it by adding the constant difference to the difference above it, then add that difference to the one above it, etc. until the value of the function is reached. This results in a procedure in which only additions are performed rather than the many multiplications which would have to be done if the function itself was evaluated for each value of x.' [33]

The difference engine was intended originally to solve two limitations of the digital, mechanical calculating machines:

1. The problem of accuracy and to prevent accumulative errors.
2. To avoid human factor errors such as wrong settings or the miscopying of results.

As the original aim of the difference engines was the preparation of errorless and more accurate mathematical and astronomical tables, they may be considered as single purpose machines.

It seems that the German Johann Helfrich von Müller (1746-1830), Captain in the Engineer Corps of the Hussar Army, was the originator of the idea of the application of the difference method with the toothed cogwheel gear mechanism of a digital calculating machine. Müller proposed as early as 1783 the construction of a difference machine to deduce mathematical tables. This machine was supposed to have a printing mechanism for tabulating the deduced results. Tabulating is the formatting of data into tables with a defined order of columns. Müller 's program did not materialize, as he failed to raise the required funding [34].

The next and better-known individual involved in the development of the difference engine was the English philosopher and mathematician Charles Babbage (1792-1871) [35]. A much-deserved full exposition and biographical study of this variegated and controversial personality exceeds the scope of this work. Suffice it to say here that in 1812 Babbage raised the idea of mechanizing the difference method as a means for deducing astronomical and mathematical tables from polynomic expressions. It is claimed that he reached this idea without prior knowledge of Müller 's work. This claim requires further investigation. Babbage, supported by the Royal Society, received a grant from Her Majesty's Government's Treasury to design an experimental model of two levels of differences, a difference engine. Like Müller 's machine, it was planned to include an automatic printed output for the deduced results. In 1822 Babbage completed a practical working prototype. Later on he tried to construct a model with six levels of differences. Yet, in spite of getting considerable government financing and also his own personal investment, he failed to accomplish the task. The prevailing explanation for his failure to construct the new model of the difference engine is that he was already preoccupied with the design of another engine, the analytical engine. From sources written by him as well as by people closely related to him, it is still impossible to conclude precisely what he meant by the idea of his analytical engine. Most scholars tend to see the written report (published in 1842) of Luigi Federico Menabrea (1809-1896) on Babbage's lecture given in Turin in 1840 as the most accurate description and interpretation of the analytical engine. But Babbage never succeeded in constructing the analytical engine. The literature contains two opinions as to Babbage's approach in the design of the analytical engine: one claims that it was a continuous improvement of a single design; the other (e.g., Hyman 1982) claims that Babbage designed several distinct models of the engine, which improved over the course of time.

Babbage was a very active and inventive person. Among his developments was a speedometer for trains, in essence, a hybrid analog-digital device using the teeth cogwheel gear mechanism. The literature portrays him as a computer 'pioneer' or 'patriarch' because of his idea of the analytical engine and, in particular, for his application of Jacquard's loom cards, the processor (mill), and for other features of his machine.

After Babbage's death, a committee was appointed in 1878 'to consider the advisability to estimate the expense of constructing Babbage's analytical engine, and of printing tables by its means'. The committee noted the 'technical ingenuity and resource' of the engine, yet it hesitated to recommend its construction and gave inconclusive recommendations. It observed that the technology of the time was lagging too far behind to construct such a machine. It also expressed doubts as to the accuracy of a device having over sixty thousand teeth wheels. In other words, the idea was premature and ahead of its time. This is an argument that already Babbage himself had advanced [36]. A different opinion as to Babbage's failure to construct the analytical engine suggests that he was inconsistent and failed because 'the enemy of the better is the best', as the Italian countess Jane Frances, Countess Harley Teleki (1836-1870) had written to him. That is to say, Babbage was in a state of confusion, improving his ideas all the time and unable to bring them to materialization, as his ideas were always 'brainstorming' in his mind and he could not transform them into practical executions.

As a marginal deviation, I claim that Babbage's failure to construct the analytical engine derives from the erroneous conceptual approach to which he was committed. This means the failure was due to his over-focusing on the teeth wheel with its great backlash (inaccuracy caused by the certain freedom that was allowed to exist between the teeth of two joint wheels). The 1878 committee expressed the technical difficulty of achieving a high standard of precision due to the complexity of the machine. Babbage was unable, or did not succeed, to make a conceptual change in order to adopt the binary or two-state technology [37]. Zuse proved that it was possible to construct Babbage's analytical engine by using more primitive technology [38]. Thus, Babbage's failure was not due to backward technology; it was psychological in nature. Babbage met George Boole (1815-1864) in 1862, among his friends was Charles Wheatstone (1802-1875), and he was familiar with the electro-magnetic telegraph, but he was not influenced by any of that [39]. After all, a person with lesser means and background than Babbage, the Swede George Scheutz (1785-1873), had by 1846 succeeded in constructing a working prototype of a difference machine that he named the 'tabulating machine', that produced mathematical tables [40]. Scheutz was induced to design this machine by an article he read titled 'Babbage's Calculating Engines' (D. Lardner, July 1834, in the *Edinburgh Review*). It provided an extensive discussion on the mechanism of the difference engine and mathematical tables. Still, there is a difference between the machines designed by Scheutz by Babbage. As a printer, Scheutz had no difficulty in implementing an output for imprinted numerical tables in his difference machine. This machine was rediscovered recently and is still in working order. Scheutz, together with his son Edward, constructed two additional models of the difference machine between 1851 and 1859. The first of these was sold to the Dudley observatory in Albany, New York, USA. The other, built by an English workshop, was sold, ironically, to Her Majesty's Government, to an office in charge of determining life insurance premium tables [41]. We may conclude that in Sweden the Scheutzes succeeded where Babbage failed [42]. Yet, although they were inspired and encouraged by Babbage, their design differed from that of Babbage.

In Europe and the USA, at the end of the 19th century, more trials were made to construct a difference engine, but these, like the previous ones of Müller, Babbage and Scheutz, did not produce a fruitful continuation. The Swede Martin Wiberg (1826-1905) redesigned the Scheutzes' difference machine in reduced dimensions and weight. A device, constructed by Wiberg in 1860, was first used for the deduction of premium interest tables. Wiberg was not content with the printed output results and designed the printing mechanism afresh. In 1875 he published, using his machine, a new set of trigonometric functions and logarithmic tables up to the seventh digit of accuracy for numbers ranging from 1 to 100,000.

In the USA, during the 1860s, G. B. Grant (1849-1917) independently developed a device by applying the difference calculations method, in ignorance of the works of others. Later, as a student, he learnt about the Scheutzes' machine at the Dudley observatory, Albany, New York. In 1871 he designed and constructed a small model of a device to deduce logarithms of mathematical functions and numbers between 1 and 100,000. Thereafter, having received a grant of ten thousand dollars, he built for the University of Pennsylvania a smaller model of a large machine that weighted more than a ton. It was displayed in 1876 at the Centenary Exhibition in Philadelphia, receiving many prizes and much praise. Another model built after Grant's machine design was sold commercially, especially to insurance companies that used it to deduce life insurance premium tables [43].

An Irish accountant, Percy E. Ludgate (1833-1922), designed and constructed several calculating devices between 1909 and 1915. Although his main interest was the analytical engine (see more on this below), he designed at least one difference machine intended to perform calculations of sixteen difference levels, namely, for polynomials of the sixteenth exponent. His want of resources and early demise prevented its realization [44].

At the outset of the 20th century, difference engines were also built in Germany. In 1909 Julius Bauschinger (1869-1934) and Johann Theodor Peters (1869-1941) constructed a device calculating two levels of differences for the deduction of logarithmic tables of numbers with an accuracy of eight figures. It seems that this was the last attempt to construct a difference engine. People interested in the deduction of mathematical tables (such as L. J. Comrie in the UK and W. J. Eckert in the USA) realized that they could attain identical or better results by utilizing calculating machines which had memory or storage registers [45].

As mentioned earlier, the counting operation is an arithmetical operation based on the difference method. We tend to see a difference or interval of one unit in the counting operation. Yet any calculating device having an iteration counting set mechanism can also perform calculations of the first difference level, if only such a device could be provided with storage registers that would enable the calculations of difference levels equivalent to the number of registers.

The Analytical Engine

The analytical engines comprised another group of digital, mechanical calculating devices founded on the toothed cogwheel gear mechanism. It bears mention that in the UK, possibly due to Babbage, the term 'engine' is used instead of 'machine'. This has to do with the idea of devices providing motive power, such as the steam engine. The English terminology of calculating devices has since been considerably influenced by terms that evolved during the Industrial Revolution (1775-1830).

Babbage had first his idea of the analytical engine by 1834. This engine was meant to analyze mathematical problems of any sort, and to 'weave algebraic solutions like the treed fashions of the loom'. This wording suggests that this engine was intended to deal with all sorts of algebraic problems, a point that many people were not aware of, for the same automatic loom could be set to all manner of different weaves and patterns. Babbage, who was far ahead of his time, had conceived computer programming! This engine was planned to have over sixty thousand gears to store one thousand numbers of fifty-three decimal digits. The above citation comparing the 'engine' and the 'loom' is significant, as it integrated a control (selecting apparatus) and a processor (mill) that applied 'operational cards' and 'combinatorial cards'—decimal punched cards, like those of Jacquard's loom (see Randell 1982 pp. 19-54).

By today's notion, Babbage's analytical engine was 'semiautomatic', as it was supposed to summon a human operator whenever problems arose. It is still hard to determine what Babbage really intended by the analytical engine. Scholars are divided on this issue. Some find in the design of the analytical engine all the elements required for the modem computer; others disagree [46]. I propose that we distinguish between Babbage's concrete achievements and his theoretical concept of the analytical engine. His theoretical concept was close to that of Leibniz, namely, seeking a universal tool to solve any reasoning problem. In his words,

> 'Whenever engines of this kind exist in the capitals and the universities of the world, it is obvious that those inquirers who wish to put their theories to the test of number, will apply their efforts so to shape the analytical results at which they have arrived, that they shall be susceptible to calculation by machinery in the shortest possible time, and the whole course of their analysis will be directed towards this object. Those who neglect the indication will find few who will avail themselves of formulae whose computation requires the expense and error attendant on human aid.' [46].

In the practical domain of designing and constructing the engine, Babbage's failures were two: one, adhering to the wheel technology—a psychological block—was technically unpractical, even today, for such a vast undertaking; the other, his sheer pedantry meant he was unable to decide and commit himself to a single working prototype of his machine. He always changed his mind before bringing to realization his previous ideas. Indeed, 'the enemy of the good is the better'.

The Irishman Percy E. Ludgate (1833-1922) in 1903, at the age of twenty, started to design an analytical machine different from that of Babbage. Professor Randell claims 'that there is little reason to doubt Ludgate's claim that his early work done in ignorance of Babbage's effort ... It is not known at what stage Ludgate learnt about the 'mathematical principles' of Babbage's machines' ([46]; Randell 1982 p. 15). However, Ludgate, in a paper delivered to the Dublin Scientific Royal Society (23 February 1909 and published in their *Proceedings* on 29 April 1909), mentions Babbage's difference and analytical engines, as well as the differences between his and Babbage's engines. In the very opening sentence of his paper he says,

> 'I purpose [!] to give in this paper a short account of the results of about six years' work, undertaken by me with the object of designing machinery capable of performing calculations, however intricate or laborious, without the immediate guidance of the human intellect.' (Randell 1982, p. 73).

Shortly afterwards, he adds:

> 'In order to prevent misconception, I must state that my work was not based on Babbage's results—indeed, until after the completion of the first design of my machine, I had no knowledge of his prior efforts in the same direction.

> On the other hand, I have since been greatly assisted in the more advanced stages of the problem by, and have received valuable suggestions from, the writings of that accomplished scholar.' (*ibid*).

Ludgate apparently worked alone on his analytical machine, but there is no evidence that he ever constructed it [47].

L. Couffignal, in his 1933 paper 'Calculating Machines: Their Principle and Evolution', claims,

> 'In 1920, Torres had a working machine in Paris, corresponding to the objective that BABBAGE had pursued. This machine consisted of the same essential elements as the Analytical Engine, but the mechanical design was quiet different, since the positioning or movement of the components was controlled systematically by electromagnetic relays. The only manual operations required consisted of entering of numbers and algebraic signs ... using the numeric and control keyboard of a typewriter... The motor then set in motion, and when the calculation was complete the result was printed by means of the type-bars of the typewriter.' (Randell 1982 p.147).

This machine, like those of Babbage and of Ludgate, did little to produce continuity or to influence the events that took place after 1935 in the development of the automatic program-controlled digital calculating machines.

Punching and Tabulating Equipment

The punching and tabulating equipment known today more as 'punch card machines' constituted an additional group of digital instrument that integrated calculating and storing components. These devices were electro-mechanical: their operation was carried out by combinations of electro-magnetic switches or by electro-mechanical switches.

The term 'punch device' derives from and is attributed to its main technological property upon which its function depends, that is to say, perforations or punch holes. The term 'tabulation', adjoined with the terms 'punch-machinery' or 'equipment', indicates the final format goal of the output of the results: these are numerical or alphanumerical data arranged in tables or arrayed in special columns to represent the data in a more distinct, legible and perceptible manner, in avoidance of reading errors or copying errors. We distinguish between the following tabulating devices:

1. Punch devices: a tool for data input, designed to imprint the required data by physically perforating holes on paper cards.

2. Reading, selecting and counting devices: a tool for collecting and processing data, intended to read the punch cards or input data from them, then to select and count the data from punch cards according to a preplanned function and to arrange the cards corresponding to the deduced information. In other words, to retrieve, classify and count the information obtained from the cards and organize it in a desirable format.
3. Tabulating devices: output facilities, aimed at printing the sorted data on paper, and set them up in tables.

Regardless of the use of electro-magnet in these devices that is a binary technology, the numerical representation base in them was still decimal [48]. Until the 1930s, the punch card equipment was most commonly used for storing, counting, selecting and tabulating statistical data. The passage from counting to other fundamental arithmetic calculating operations is simple [49]. Practically, it is very easy to use the punch equipment to get the total sum of counting derived from the last counted operation immediately. In the 1930s, the production of multiplication calculating components for punch equipment began that still rested on the toothed cogwheel gear mechanism [50].

It was Babbage (1834) who first integrated the punch card as a means for storing numerical data and instructions in a calculating device. Yet it was Herman Hollerith (1860-1929) who harnessed the punch card for this purpose in 1891. According to one of the versions of the story that seems more reliable, it was John Show Billings (1839-1913) who first inspired Hollerith with the idea of utilizing the punch card for sorting out the USA's 1880 census data:

> 'There ought to be some mechanical way of doing this job, something on the principle of the Jacquard loom, whereby holes in the card regulate the pattern woven.' [51].

According Hollerith's own version, his suggestion to utilize the punch card was indirectly influenced by observing conductors punch holes in travelers' paper tickets. Between 1883 and 1889 Hollerith developed a comprehensive system, incorporating census punch cards, which enabled the mechanical, or rather mechanized, collecting and processing of census data into the required statistical information. The issue of patent or idea priority, such as those of Hollerith and Billings, although fascinating by itself, exceeds the scope of the current work. Suffice it to say that it bears note that Hollerith was the first to employ practically the electrical switch, known also as the electro-magnetic relay, for calculations, or more precisely for counting and sorting digital information.

In Hollerith's device the reading of data was performed by putting the punch card over a plate of concave surfaces filled with mercury. Against the punched card were pressed tiny electrical electrodes that formed an electrical circuit which, once it passed through the punched holes of the card and reached the mercury, increased the count at special electrical counters accordingly. Sorting the information from the punch cards was performed by sorting machinery—sorters—applying binary logic and technology by means of electro-magnetic circuits.

As an inventor, Hollerith is typical of the developers of the automatic program-controlled digital calculating machines of the period 1935-1945 (for details see Part II). Hollerith studied mine engineering at Columbia University. Between 1879 and 1883 he worked in the USA Census Office. By 1889 he got a patent for his tabulating machinery, which was adopted for the National Census of 1890 by the Census Bureau. Unlike the developers of the automatic program-controlled digital calculating machines of 1935-1945, Hollerith was also successful as an entrepreneurs and a businessman. The contemporary IBM firm is an outcome of merging of several firms, one of them being Hollerith's original firm the Tabulating Machine Company founded in 1896.

As to any question of Hollerith's awareness of Babbage's efforts, this remains controversial, though Babbage's work was known in the USA, as is well evidenced by the publication of the 1873 Annual Report of the Smithsonian Institution. [52]

Following Hollerith's technological breakthrough in harnessing electricity and implementing the electro-magnetic switch for calculating, James Powers (1871-1927), inspired by Hollerith's success, developed in 1908 tabulating punch devices based only on mechanical components. In 1911 Powers established his own firm which later on merged with the Sperry-Rand Company. The firms of Hollerith and Powers expanded throughout the world *via* daughter firms.

An important piece of work on punch tabulating equipment was accomplished in Austria by Otto Schaeffler (1838-1928) and Gustav Tauschek (1899-1945). Schaeffler, an expert in telephone exchanges, became Hollerith's Machines agent in Austria as a result of a meeting held in Vienna in 1891 when Hollerith was there on his honeymoon. Schaeffler provided extensive flexibility to Hollerith's machinery with electrical wiring between the various devices, integrating them under a control switch board by the use of sockets and plugs, similar to those used in manual switch boards. He obtained a patent for it on 10 May 1895. Hence, Schaeffler's design has a primary programming capacity.

By the end of the 1920s, the punch tabulating equipment was applied to commerce and accountancy; it was also used in several academic institutions, mainly for administrative and statistical ends [53]. By 1940, this type of machinery was also used for code deciphering: in the USA in 1940, in the UK in 1941 and in Germany in 1943 [54].

During the 1920s, IBM developed a tabulator with printed output. In 1936 IBM started to manufacture a mechanical multiplier performing multiplying operations on data set up on two punch cards. The Deutsche Hollerith Maschinen Gmbh (the daughter firm of Hollerith's company), developed in 1936 the D11 tabulating machine that had a 'programming board' of sockets and plugs, enabling the performance of the four basic arithmetical operations. This machine also had a random-number generator and a storage device. In 1938 IBM announced electrical punch equipment, the first of its kind in the market, permitting direct addition and multiplication.

Integrated and Synchronized Calculating Devices

This group of calculating devices is an integration of several off-the-shelf commercial items. The uniqueness of the structure of these devices is in their specific integration of the various components required for synthesis, timing, synchronizing and control without altering the basic qualities of the integrated devices. In the 1920s several such designs were introduced to perform a few coordinated operations of calculations or accountancy. The integration usually consisted of an electric typewriter connected with punch equipment, or a regular office digital calculating machine combined with accountancy equipment. The Spanish inventor Leonardo Torres Quevedo (1852-1936) was one of the first to contribute to this field in the 1920s. Similar integration was accomplished by joining two or more office calculating machines under a single operating and control system. In 1928 at Columbia University, for example, such integration was applied to adapt tabulating equipment for scientific calculations. The late 1930s and early 1940s saw an increasing tendency to synthesize several differing facilities to get a device with new and unique properties, such as calculating interpolations, or differences, for deducing mathematical astronomical tables. This trend is demonstrated particularly in the accountancy machines which had memory registers, such as the National-3000 model. What characterizes these designs, such as those of the IPM (Institute for Applied Mathematics of Technische Hochschule in Darmstadt, Germany) from 1943, is the application of electrical communication (cables) and electro-magnetic switching. Also, because of the need for synchronization, these devices feature a governing mechanism of one kind or another, resting on either the typewriter or an accountancy machine. Typewriters and tabulators could function also as input and output devices for the deduced results. The complexity of the integrated synchronized devices demanded the application of an electrical motor as the driving power. Sometimes the control mechanism was modified from punch card machines to teleprinters, but these were the exception. The punch cards were generally used as the means for the input of numerical data. In integrated synchronized devices the most common control mechanism was the switch board, like that of the manual telephone exchange, comprised of sockets and plugs creating cross-connections by certain settings of the plugs in the sockets. Sometimes the electro-magnetic switch was also used for control. The electro-magnetic selector is a scaled-down model of the automatic electro-magnetic telephone exchange, enabling the diversion of the operations of the electrical pulses to predetermined operations. It must be emphasized that the electro-magnetic selectors or switches are of a pre-determined, fixed, unchangeable format program. Hence, once these selectors were designed and constructed, the governing and operating program was imprinted in the hardware of the device, inalterably presenting a serious obstacle by ruling out general purpose applications. It is exactly due to this quality that these devices differ deeply from the automatic program-controlled digital calculating machines developed in the period 1935-1945, that were built as multi-purpose: they were able to alter their program without physical changes to the hardware.

Partial Differential Equations

One set of problems that caused distress to mathematicians and physicists was that of partial differential equations. Generally speaking, we can classify linear partial differential equations into three groups: parabolic, elliptic and hyperbolic. To the first group belong problems of the conduction of heat; to the second, problems of electrical potential difference (voltage) on the surface of the conductor; and the third, problems in aero-fluid-hydrodynamics. These three groups of problems have considerably different mathematical and practical characteristics, due to their different physical behavioral qualities. In England, Douglas R. Hartree had some success with the first group of problems. He also conceived that his limitation as to the second group of problems was in to how to treat them by the differential analyzer. This limitation was partly because Hartree was unaware of new mathematical works that arose out of numerical perceptions as conceived by Courant, Friedrichs and Lewy, as was to develop later on in 1947, within the discipline of Numerical Analysis. Hartree and his colleagues Manchester and in Cambridge studied the complex physical and engineering phenomena by means of calculating devices and not with experimental instruments. Not one of the eminent and famous scholars and scientists of physics, mathematics, chemistry and other domains in the 1930s used this type of calculating device. In other words, no major discovery until at least 1935 appeared due to the use of any sort of new mechanical calculating device.

Analog Calculating Device

Background

The term 'analog' is derived from the Greek *'ana-logon'*, from *'ana'*, 'according to' and *'logon'*, 'ratio', and was originally used by the Greeks to mean similarity in proportional relationships. This may be similarity between two figures (say, triangles) that differ in scale or between two quantities, one of which, though unknown, can be calculated if its relation to the other is known to be the same as that of two other known quantities. Thus, if 2:4 :: 4:x, then x=8. In the analog this means the principle, as with a scale map or a diagram, of constructing a reduced scale model of the particular system which is to be represented, calculated or measured. A simulation is then created in a desirable scale, usually smaller and thus more manageable. In this sense, analog serves also as a tool for measuring similarity against identity. The analog calculating device solves certain mathematical and physical problems in which quantities are represented by physical magnitudes, distances, relations, voltages and currents capable of continuous change. The solutions to problems are obtained by creating changes in a situation or process analogous to that of the problem and then measuring the results.

The desired scales and calculations of the analog devices are obtained by means of components named 'integrators' and 'analyzers'. The integrator consists of a smooth (toothless) wheel propelled on a moving flat disk. The location of the wheel on the disk can be altered at will, thus creating the desired scale of calculation. According to the desired location of the movement of the wheel on the disk, the final result could be deduced by the integration of all the scales applied between the reduced model and the system to be measured or calculated [55].

Until 1935, most analog calculating devices were mechanical. In 1937 in the USA and Germany electrical analyzers were developed for the first time. The construction of the first electronic analyzer model was completed in Germany by 1942 [56].

The development of this type of device is of no primary interest to the matter at hand. They are mentioned here only to assist in clarifying the issue of what components of these devices could be applied to the automatic program-controlled digital calculating machines. B. O. Williams' PhD dissertation (1984) strongly asserts that ENIAC (1943-1946) used components designed for the Rockefeller Analyzer, developed by Bush at MIT by 1942. Williams' claim is disputed, particularly as to how much the ENIAC team was assisted by those components designed at MIT and elsewhere. Yet, even assuming that this claim is correct, it relates only to the practical construction and not to the sole crystallization of the idea and the design of the electronic digital program-controlled calculating device (ENIAC).

In the book by Horsburgh (1915) titled *Napier Tercentenary Celebration* that commemorated the development of the logarithms by Napier (1614), Section G—'Other Mathematical Laboratory Instruments'—names a group of calculating devices that can be included in the analog calculating group, including: integraphs, integrators, planimeters, differentiators, harmonic analyzers, tide predictors, conographs, pantographs, photographic calculators, equation solvers, and mechanical aids in periodogram work [57]. Until the early 1940s the name for these analog calculating devices, as appears in Horsburgh's book, was 'continuous calculating devices'.

In the main, analog devices were developed for unique and specific objectives. Analog devices were known in the past in ancient Egypt, Greece and Rome, such as the odometer and the Aristotelian geocentric system model. Later examples are the mechanical clock (12th century), the Copernican solar system model, the barometer and the thermometer (17th century). However, only during the 19th century did physicists reach sufficient levels of sophistication to describe by mathematical equations the functioning of rather complex mechanisms. In other words, they learned to imprint abstract ideas in hardware. They also succeeded in performing the reverse operation, to wit, to carry out the transition from a given set of equations to design a device or tool that by its movement expresses a correspondence to those equations. Designer of analog devices had to determine the kind of movement they were interested in, and then to find the tools whose operating rules are analogs, i.e., parallel, to those desired. Though the literature mentions the slide rule as an example of an analog calculating device, I shall refrain at this stage from doing so, as a separate section is dedicated to it.

The outset of the modem tradition of the analog calculating devices is the construction of the Planimeter, a tool designed to calculate the surface planes of bounded or enclosed curves. It seems that the first version was constructed in Germany in 1814 by Johann Martin Herman. During the 19th century there appeared many improvements of that version, or of independent designs; among the better known are those of James Clerk Maxwell (1831-1879) of 1855 and James Thomson (1822-1892), brother of Lord Kelvin, who exhibited an improvement of Maxwell's device to the Royal Society in 1876. Maxwell also defined the laws governing these devices in his 1855 paper, 'Description of a New Form of the Planimeter, an Instrument for Measuring the Areas of a Plane Figures drawn on Paper' [58].

It was Lord Kelvin (Sir William Thomson, 1824-1907), who designed the integrator of a moving wheel on a disk, the component enabling the integration to sum separate quantities and providing flexibility in changing ratios of scales or to determine variables. This vital component, without which integration is impossible, also rests on wheel transmission, but in this case these are toothless wheels moving perpendicularly to each other. In 1902, Leonardo Torres y Quevedo designed an integrator founded on a toothed cogwheel gear mechanism, but that was an exception. Kelvin designed a 'Harmonic Analyzer' and a 'Tide Predictor' that were no more than hardware expressions of equations representing phenomena of periodical, harmonic or wave motions appearing in the famous 1807 paper of Jean-Baptiste-Joseph Fourier (1768-1830) on the analytical theory of heat and his famous 1822 book *Theorie Analytique de la Chaleur*. Kelvin tried to extend the application of the developed devices to differential problems, but with no significant success. This was exemplified in his 1876 paper prepared for the Royal Society: 'Mechanical Integration of the General Linear Differential Equation of Any Order with Variables Coefficients'.

The same ideas were conceived also by the American engineer, V. Bush during the 1920s, without former knowledge of Kelvin's work. The technical difficulty that Kelvin could not overcome was related to the friction coefficient between the movement of the integrating wheel on the disk and the motion of the disk itself. The inaccuracy was the result of skating of the wheel on the disk, limiting the number of integrating elements that could be combined, and thereby diminishing the number of variables that could be set. The famous American physicist Albert Abraham Michelson (1852-1931), who measured with great precision the speed of light by means of an optical interferometer, in 1897 at the University of Chicago constructed with Samuel W. Stratton (1861-1931) a device capable of carrying out an adding operation of a harmonic analysis, which excluded the inaccuracy of Kelvin's devices. The Michelson-Stratton device rested on the integration of the released energies of a spiral spring enabling the solution of a Fourier series of twenty variables (organs). Consequently, they constructed a device to calculate eighty organs. Stratton left Chicago and moved to Washington to found the American Bureau of Standards and subsequently become President of MIT. At MIT he was sympathetic and helpful to Bush's efforts. Bush picked up and proceeded with the development of differential analyzers, following the path that Kelvin had set out. Bush had already constructed in 1919 a measuring wheelbarrow that resembles that of Archimedes, but while also taking into account the slopes of the terrain in its path. In 1927, Bush, supported by Gage and Stewart from the electrical engineering department at MIT, designed and constructed a mechanism that did not just solve problems which were an analysis of integrals, but also, with the aid of several such mechanisms joined together, enabled the solution of the practical problems of electrical current, continuous pulses and deduction of integrals. The basic element in this device was the standard electric companies current meter, which is just a means providing a result of an analysis of a solution of an integral of two factors—current and potential difference (voltage)—as a function of time. Bush and his associates understood that it was possible to set up on the electric current meter's counter, with some modifications, other arbitrary variables to express the function of time that would be represented by relative potential differences in voltages to the current's strength. Analog calculating devices were also developed in other places in the USA, for example at the Chase School of Applied Science, Cleveland.

Bush focused upon the development of the Net Analyzer, enabling engineers to solve complex problems in real time, as expressed in the alternative current electric supply nets, in scaled-down simulations of electric power networks. Norbert Wiener (1894-1964) participated in this program. Between 1927 and 1942, MIT made great strides in the field of developing analog calculating devices, though work on some digital designs took place as a lesser priority. Bush describes in a 1931 paper, 'The Differential Analyzer, a New Machine for Solving Differential Equations' [59] a totally mechanical analyzer. Only by 1942 did Bush and his associates at MIT complete an analyzer, dubbed the Rockefeller Analyzer after the fund that had financed its development, driven by electrical motors with some two thousand radio vacuum tubes. It was controlled by punch paper tape in order to enable a programming capacity and flexibility far beyond what was then accepted in analog calculating devices.

MIT and General Electric cooperated in developing a Net Analyzer in the early 1930s. In 1935 two twin differential analyzers, made according to Bush's design, were completed, one for the Ballistic Research Laboratories at the Aberdeen Proving Ground MD, and the other for the Moore School for Electrical Engineering at the University of Pennsylvania. These were giant machines, each weighing about one hundred tons and having dozens of electrical motors and transmission gears. Following Bush's 1935 design, differential analyzers were also constructed in the UK and the Soviet Union. An original difference analyzer was designed and constructed in Cambridge, UK by F. C. Williams. Various difference analyzers were built all around the world.

In Germany, an independent development of analog calculating devices took place. By 1914, Udo Knorr (1887-1960) designed the 'Fahrdiagraph' to determine railway timetable schedules as a function of the towing power and the structure of the cross-section of the railways. This device was a true differential analyzer with feedback. It predates the machines developed by Vannevar Bush. Knorr's PhD dissertation, written in 1921, was about his device. Although this design was constructed and implemented mainly by the German railway authorities, it did not produce momentum in the design of more sophisticated analog devices in Germany. One of the incentives for the development of analog instruments was World War I. During the war the range of the naval guns increased from less than five kilometers to more than twenty kilometers due to the extensive development of ballistics in Germany. That spurred the development of some analog devices for calculating fire-tables for ranges and angles of elevation of the guns of battleships. This type of device was developed not only in Germany but also in the USA; I suspect that the British navy must also have possessed such instruments. Harmonic analyzers were also developed in Germany by 1915 to determine partial vibrations according to the Fourier series [60].

By 1928, Alwin Walther (1898-1967) had established the *Institut für Praktische Mathematik* (IPM) at Darmstadt Technical Higher Education

School. The object of this institute was to broaden the mathematical knowledge of engineering graduates. Walther saw a big gap between the mathematics needed for the solutions to engineering problems and the low mathematical training provided to engineering graduates. This trend was previously noted in the USA for training electrical engineers by German émigré C. P. Steinmetz at the beginning of the 20th century. Walther emphasized the development of new mathematical perceptions for engineering. Many mathematical problems were not possible to solve just by setting equations. Some numerical solutions are possible only by using methods of iterated approximations. Applied mathematics was the attempt to develop such approximation techniques of calculations suitable for engineers. The objective of practical application was supported by mathematicians and encouraged the development, improvement and dissemination of digital and analog techniques to problems that had been previously impossible to solve. Walther said, ‘Engineering students must be capable of dealing with mathematics not only as an accurate formalism enabling them to sum up the scientific knowledge, but also—as much as possible—as a vivid and interesting subject like other auxiliaries of intellectual activity’ [61].

Under Walther’s guidance, the mathematical calculating laboratory was founded, with the extensive use of auxiliary facilities. In addition to the common methods of solving problems, students in their initial term of study were expected to acquire experience and practice by applying digital and analog equipment for graphical integrations and approximations. Walther attached to the institute a mechanical workshop to construct instruments at will and as needed. During the period of 1930-1945, many digital and analog devices were designed at the IPM; it has issued a catalogue that exceeds the scope of the present study. The IPM also trained woman calculators (in German *Rechnerinen*) from the university candidates. In its prime, the IPM employed eighteen scientific graduates and assistants as well as an auxiliary staff of some sixty people who prepared drawings and diagrams, etc. There were more than fifty calculating machines at the institute. The equipment used at the institute included machines of various types and brands, among which were ‘entirely automatic’ electrical calculating machines and an accountancy machine combined with an electrical typewriter that was experimentally applied for calculations by the institute.

A device similar to that designed by Bush was constructed at IPM between 1939 and 1941 for ballistic calculations to produce artillery firing tables. An independent differential analyzer was constructed in Oslo and, after

Norway's capitulation, the Germans imitated it, constructing one model at IPM and another at Danzig Technical Higher Education School.

World War II saw a significant acceleration in the development of analog instruments in Germany, especially in the aircraft and V-weapon industries. The IPM turned out to be the top approval authority for all types of calculating device projects of the Third Reich. Even Zuse's Z-4 was inspected by H. J. Dreyer and A. Walther of the IPM in Berlin on December 14, 1942 in the basement of Zuse's parents' house. Wilfried De Beauclair claims that the IPM also provided various components to Zuse. A differential analyzer was developed at the IPM (1941-1943) that had an electrical motive power system and automatic followers of photo-electric cells. It had similar properties to those of Bush's Rockefeller Analyzer of 1942 [62]. By 1942, the first electronic analyzer in the world was already in operation in Germany, designed and constructed by Helmut Höltzer (or Hoeltzer). It was constructed in secret under cover of Wemer von Braun's office, and in contravention of the Third Reich's official policy that opposed and prevented the development of such devices. The developers of differential and integral analyzers were also involved in the development of automatic tracers and followers of curves as well as to plot automatically the deduced curves solved by the machine. Photo-electric cells were applied for this purpose, ones that had appeared on the market in the early 1930s. Norbert Wiener of MIT suggested in 1940 to develop an analyzer for a particular group of integrals that applied optical principles to a movie projector and photographic films.

The Slide Rule

The slide rule is a calculating tool that applies the principle of logarithms to perform most of the calculations done by means of logarithms. At its outset it was used only for multiplication and division. The development of the slide rule advanced in congruence with the development of logarithms. In 1620 Edmund Gunter designed the logarithmic 'line of numbers', on which the distances were proportional to logarithms of numbers indicated, known as Gunter's Scale. The multiplication or division operation was carried out by adding or subtracting the corresponding distances measured on the 'line of numbers' by a pair of compasses. This instrument was subsequently used in navigation. In 1628 Edmund Wingate published the 'Construction and Use of the Line Proportion of Ratio Lines' that resembles Gunter's Scale. It was a rule in which the spaces on one side indicated numbers, while those on the other side indicated the mantissas of these numbers (the part of a logarithm that follows the decimal point.). William Oughtred (1574-1660), an English clergyman, designed the slide rule circa 1622. The written description of it was not published until 1632 in his ‘Circles of Proportion’. Independently, Oughtred’s pupil, Richard Delamain, published a pamphlet entitled ‘*Gemmologia*’ (or the Mathematical Ring). It was a description of a circular slide rule, while Gunter’s Scale had no sliding parts. Only by 1654 did Robert Bissaker construct a slide moving between parts of a rigid stock. Subsequently many improved the slide rule, among them Newton, who devised a system of concentric circles to solve equations. During the 17th century the slide rule attracted little attention in England or in Europe. In the 18th century, however, its value began to be recognized. By 1748 the American George Adams constructed a spiral slide rule, which had higher accuracy. In 1787, William Nicholson (1753-1815) described the types of slide rules then known. Nicholson suggested noteworthy improvements enabling the construction of a slide rule of more than six meters in length. He also designed a spiral slide rule.

Improvements in the direction of increased accuracy in gradation were initiated by Matthew Boulton and James Watt from about 1779 in conjunction with the design of steam engines (*Britannica* 1974 11, 653). Amedée Mannheim (1831-1906), a French artillery officer, developed in 1859 what may be considered the first modem slide rule. He set the standard for the slide rule that bears his name. The standard included, among others, improvements in scale without any increase of the size; adapting slide rules for specialized branches of science; and improvements upon the mechanical efficiency of the device. In 1886 the Germans Johann Christian Dennert (1829-1920) and Martin Pape (1834-1884) introduced a scale on white celluloid, instead of on wood, brass or ivory, affording much greater distinctness and legibility, which was later adopted almost universally.

Before 1890 slide rules had been made only in the UK, Germany and France, but at that time William Cox initiated the manufacture of slide rules in the USA. He introduced a revolutionary construction providing scales on both sides of the slide rule. A glass indicator made it possible to refer to all the scales on both sides of the rule simultaneously.

The historian of mathematics Florian Cajori (1859-1930) states in his 1909 *A History of the Logarithmic Slide Rule* that in the USA between 1880 and 1886 the slide rule was almost unknown and the use thereof was uncommon [63]. He adds that there is no evidence whatsoever that the slide rule was popular in Europe during the 18th century [64]. In the second quarter of the 19th century the use of the slide rule in England declined consistently. For instance, De Morgan complained in 1842 in the *Penny Encyclopedia* under the entry 'Slide-Rule' that 'the tool is underestimated' [65]. Cajori in his 1909 book lists 256 slide rules designed since 1800 and provides a chronological table of all the slide rules designed between 1620 and 1909 [66].

In Horsburgh (1920), there is an interesting statement concerning the type of instruments that is most desirable for an engineer:

> 'In most of the calculations required by an engineer only three or four leading figures are needed, and the rest of strings of digits is unimportant. If merely two or three significant digits are required, the small slide rule is best, or else graphic methods are adopted.
>
> However, if higher accuracy is required then the long slide rule will suit for this purpose much better. Then if there is still need for higher accuracy, then the logarithmic tables of seven or eight digits are available and this is what most of the people will make use of. Solution by means of a tabulator is long, laborious and mentally exhausting more than any work with a mechanical calculating device. In special occasions, with equations adapted particularly for logarithmic techniques and require high standard of accuracy, the passage to the long slide rule and the application of logarithmic tables is the best. The advantage of the mechanical calculator is in production of tables, in which speed, accuracy and the execution of huge amount of laborious calculations of the same sort is needed.' [67].

Horsburgh adds:

> 'Hence, from the latter point of view the scope for the use of calculating machines in engineering and commerce is very great... Till recently the mathematician felt that calculating machines were created by beneficial providence - in the form of manufacturer - for his exclusive enjoyment. Now, however, they are widely used by engineering and commercial firms.' [68].

Nevertheless, Horsburgh writes that the most abundant machine in use was the adding machine, indicating the growing tendency of mathematicians to avoid the use of logarithmic calculations, and apply instead the natural trigonometric functions tables with the assistance of a calculating machine. He notes that the calculating mechanical machines, compared to the punch equipment, were too expensive. At the IPM, Darmstadt, a slide rule was developed in the 1930s, known as the Darmstadt scale rule. It achieved considerable commercial success, being manufactured by three firms. This slide rule was very handy to operate and became popular among students and engineers. In 1935 J. Mauchly (initiator of ENIAC) actively encouraged the use of the slide rule among university graduates in the USA, but without meaningful success. A document in the Mauchly collection at Van Pelt Library at the University of Pennsylvania provides some notion as to the use and grasping of the slide rule by students:

> 'Many students never learn to use the slide rule, but waste many hours with fruitless calculation because of a belief that the complexity of slide rule can be mastered only by a superman.' [69].

Two other 'computer pioneers', Atanasoff and Stibitz, were influenced by slide rules during their childhoods, as will be elaborated in Part II.

Intermediate Summary

Before 1935, calculating instruments did not possess any control system or program enabling the device's object to be changed without causing any changes in its physical structure. Still, calculating devices up to 1935 had three vital components required and implemented in automatic program-controlled digital calculating machines, as they are now defined. That is to say, most digital calculating devices until 1935 contained the following components:

1. Input component: usually, data by means of keys were fed into it for calculations.
2. Output component: normally, a display window or a paper printout by a printing mechanism or a typewriter, on which the deduced final or intermediate results were displayed.
3. Calculating component that almost always rested on the toothed cogwheel gear mechanism and on the decimal representation base.

Some calculating devices (office calculating machines and cash registers) had a storage component with up to six registers. The punch equipment enabled a considerably larger storage capacity by keeping the punch cards.

Yet the punch equipment and other calculating means lacked a control component capable of operating according to a plan or a sequence of instructions that could be altered at will. Furthermore, these devices lacked a communication system that could maneuver and transfer data and instructions among the various components for the input, processing, storage, retrieval and output of data and results.

CHAPTER TWO

MEANS, TECHNIQUES AND IDEAS FOR CALCULATIONS

Introduction

In this chapter I will discuss those means, techniques and ideas that could be implemented during the 1930s in the automatic program controlled digital calculating machines. The means that could be incorporated during the 1930s in the automatic program-controlled digital calculating machines are as follows:

1. Office, digital calculating machines—manual or automatic based on the teeth cogwheel gear mechanism. In the 1920s and 1930s, the term ‘automatic’ related to: (i) either to the motive power (mechanical or electrical); (ii) or to the execution method of multiplication or division (repeating operation of adding or subtracting, or the performance of the multiplication by means of an mechanical or electrical imitation ofthe multiplying or logarithmic tables); (iii) and possession of some sort of storage facility, (registers, for storing intermediate or the final results for additional calculations).
2. Punching and Tabulating-Equipment—implementing a binary technology for counting, sorting and storage of large quantities of data.
3. Counting devices of elementary atomic particles or cosmic and electromagnetic radiation—based on vacuum or low pressure gas filled tubes and electromagnets.
4. Storage and regulating means—based on the punched paper tape or cards, mechanical or electromagnetic devices, such as telephone central exchanges, or magnetized-tape/wire, optical apparatus founded on the photo electric effect, and electronic devices based on vacuum or gas filled tubes. At that period an extensive research was conducted (particularly by the KODAK company in the USA), for the application of the photographic film as a means for storing and retrieval of information.

5. Input and output means—based on keys or push-buttons such as electrical typewriters teleprinters, as well as catholic-ray-tubes and photo-electric cells, punched paper tape and cards.
6. Control means—that were then based mainly on the punched paper tape or card, although electro-mechanic and electromagnetic control systems were available, as well as experimental models of electronic control systems (particularly in telephone exchanges).
7. Communications means—the most abundant of these were the electrical cables, switches and telephone exchanges.

The techniques and ideas that could be implemented during the 1930s, in the automatic program-controlled digital calculating machines, are these.

1. The ideas of numerical base notations/representations and techniques for passage from one base to another.
2. The idea of control and automation.
3. The idea of difference and iterative (Newton-Raphson) calculation technique.
4. The symbolic Boolean logic and Algebra.
5. The idea of process, format, algorithm.

The Idea of Numerical Representation

The numerical method of calculating rests on quantitative values that could be counted or enumerated in order to accumulate and perform with them and on them the basic arithmetical operations such as addition, subtraction, and *via* these multiplication, division and all that derives from all this. The counting relates to the concrete (perceptible) tradition of calculations. It is the most fundamental arithmetical operation developed in all the ancient civilizations. In parallel, evolved techniques of recording, to preserve the information and the manner by which those operations of calculating are to be carried out by the operated quantities. In ancient Accad and Shomar, the numerical notation was based on the number 64 as its base. That is to say, that it was a fixed sign code having 64 different signs to represent 64 part and distinct quantity values. In ancient Egypt the numerical representation was on the base of 12. The American Indians used the base 20 for their numerical notation. The binary notation, founded just on two signs, was found among the Aborigines tribes in Australia. The binary notation was well known too in the language of the Papuan people, at the adjacent beaches of New Guinea and evidently also in China some 4000 years ago. Some explain the abundant trend of applying the decimal notation due to man's ten fingers. That is not necessarily so. In fact, the decimal notation was introduced in Europe only by 1202, and was accepted, after severe resistance only in the 16th century. Moreover, the decimal notation, customary today in the modem world, the one that includes the numerical place notation in which the zero serves the function of a 'place-keeper' of an absent value quantity digit, was imported to Europe from North Africa by Leonardo of Pisa (Fibonacci), also by 1202; its origins are Hindu-Arabic.

The Binary Notation/Representation

Historians of mathematics are of the opinion that the numerical counting and calculating techniques developed some five thousand years ago [1]. Phillips (1936) states, that the binary notation served as the oldest notation to perform calculations. In the literature many sources ascribe to Leibniz the 'invention' or 'discovery' of the binary system (the more apt expression is 'adopt'). Needham (1958) provides an interesting account on this issue. Almost in front of every respectable Chinese temple, a mysterious scroll was displayed, with three vertical colunms of lines of varying lengths. These scroll line markings seem to be the 'Kora', a binary numerical notion, since 2300 years B.C. [2]. Francis Bacon has written in 1623 an assay dealing with the application of binary Alphabetic notation for concealment of written messages. M. Gardner (1974) describes an application of a Chinese binary code, related to the period of the first Chinese dynasty (Hsia 2205-1766 B.C.), in the *Book of Changes* or *Ye-Jing*. It offers an arrangement of 64 hexagrams (patterns of combinations in binary representation on the base of hexa—in Greek six) arrayed in straight or fragmented vertical lines. Father Joachim Bouvet, of the Jesuit Order in China, introduced Leibniz with what is known as the Fu-Xi series (founder of the first dynasty of Chinese Emperors). Bouvet claimed, that in order to understand the real meaning of the markings of the Hu-Xi series, one may replace the full straight lines by the digit '0' (zero), while the fragmented lines are to be replaced by the digit '1' [3].

Leibniz presents a view close to that reflected in that series, in his 1679 essay, 'Of an *Organum* or *Ars Magna* of Thinking', in which he wrote the following.

> 'The most powerful of human faculties is the "Power of Thinking", ... although the things which are conceived are infinite, yet it is possible that those conceived through themselves are few; for infinite thinking can be out of the combination of few. Indeed, this is not only possible, or probable; for nature usually does as many things as possible with the smallest possible

> number of assumptions, that is, it operates in the simplest way. It may be that there is only one thing which is nothing, or privation. This is made clear by an admirable simile. When we count, we commonly use the decimal system, so that when we arrive at ten, we start again from unity. That this is convenient, I do not dispute; meanwhile, I will show that it is possible to use in units place the binary system, so that soon as we have reached two we start again from unity, in this way:
>
> 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
>
> 0 1 10 11 100 101 110 111 1000 1001 1010 1011 1100 1101 1110 1111 10000
>
> It is enough to have noted in what a wonderful way all numbers are thus expressed by unity and nothing ... every idea is analyzed perfectly only when it is demonstrated "*a priori*" that it is possible...since, however, it is not our power to demonstrate the possibility of things in a perfectly "*a priori*" way that is, to analyze them into god and nothing ...' [4].

Leibniz claims there that it is possible to reduce all the linear movements of any geometry just into two movements, one straight line and the other a circle.

Early Binary Notation Technologies

The application of binary notation to mark quantities (counting and enumeration) and calculations is relatively a later outcome. The binary representation in technology existed for more than ten thousand years in weaving, a technology known to all ancient civilizations. The weaving is binary counting—addition, in which in parallel is produced and stored the output—the perpetuated woven pattern cloth. An additional example for the binary technology are the many sorts of apparatus installed in the various automata that emerged at a certain stage during of the 12th and 13th centuries; for instance, in clocks and music boxes [5]. The pegged cylinder or drum, in which the protruding pegs, pins or nails are inserted, in concrete manner express the principle of binary technology. The drum, in general, is an information storage device, related to retrieval and reproduction of a particular type of information such as sounds or operations. During the rotation of the pegged drum, the protruding pins strike levers, pieces of metals or other producing sound mechanisms, such as opening of valves, to enable the stream of pressed air in the pipes to blow the organ's flutes [6].

Polybius Megalopolis (200-118 B.C.), the Greek historian of Arcadia, reports that in ancient Greece of 300 B.C. the binary notation technique was applied for communication and delivery of massages by means of visual signals. It is a telegraph (derived from Greek 'tele'—'far' and 'graphein'—'to write', in today's terminology a 'Semaphore'—meaning in Greek a 'bearing a sign'). This telegraph preceded by more than two thousand years the application of Bi-Quinary base notation, (using both the binary and quinary—five—bases) that Stibitz used in the BELL 'computers' by 1938. The operating technique of the Greek telegraph was based on a code formed by placing the 24 letters on a grid of five horizontal rows and five vertical columns, so that the first letter, Alpha, fell on the first row of the first column and the last, Omega, on the fifth row of the fourth column. To signal all the 24 positions, ten vases were held in reverse behind two low walls separated by few meters. In signaling Omega, the sender would place five vases on the left wall and four on the right [7]. At night torches were used instead of the vases.

The same method was used by medieval prisoners to communicate through the wall of adjoining cells. Today's 26-letter alphabet was contained within the five-by-five pattern because 'I' and 'J' were initially one letter. The numbers were tapped out in series of pairs, 1-1 indicating 'A'. This idea transferred the code from purely spatial configuration to one involving time. In 1551 an Italian mathematician, Girolamo Cardano, suggested that five torches on five towers could be used to spell out letters, with all five beacons figuring in the code as 'light' or 'dark'. The invention of the telescope in the 17th century stimulated interest in visual signaling. Several fresh proposals were put forward by such men as the English physicist Robert Hooke, though none was immediately developed. Two optical telegraphs systems were built, one in France (1794) by Claude Chappe (1763-1805) and one in England (1795) by Bishop George Murray (1761-1803). Chappe and his older brother invented in 1791 and applied the name telegraph to their two-arm semaphore system. Each arm can be made to assume seven angular positions 45 degrees apart, together the two arms could display 49 positions to represent the letters of the alphabet and other symbols [8]. Murray, established in the British Admiralty a visual system called a shutter telegraph, consisting of six solid shutters, each independently rotatable 90 degrees on a centered horizontal axis, arranged in the three-by-two pattern. The code, governed by decisions as to how many and which shutters to open simultaneously, was similar to that of Cardano's five 'light' and 'dark' torches except that a larger number of combinations was possible (64 as compared to 32) [9].

The quantitative representation of the Roman numerical notation is on the quinary—five (in Roman V) base. The number 4 is represented as 5 'V' minus 1—'IV', while the digits 6 to 8 are represented as 5 plus 1, and 2 and

3 respectively—VI, VII, and VII. Likewise, the digit 9 is represented as 10 (X) minus 1—IX etc.

A mechanical grinding device (pestle) from the 10th century propelled by water power wheel, is also an unconscious application of binary technology. This device exists in two states, one in which the pestle is elevated upwards to a certain height, to gain potential energy, the other, the state of downfall, accumulating kinetic energy, and the execution of the crushing-grinding action. Possibly, such a grinding device has inspired the appearance of the steam engine piston in 1695, in which the two state technology is clearly illustrated. The term and concept of 'state', though, deserves a critical analysis. I will refrain of doing that. It seems that the 'state' issue started to be debated during the 19th century in efforts to describe the physical and chemical properties of substances.

Binary Notation in Computing

Apparently, it was Leibniz (1679) who enhanced the plausibility of a design of a binary calculating device, using metal balls to represent binary digits (bits) [10]. It seems that Babbage applied for the first time the binary notation in a calculating device. (The analytical engine was then called 'Calculating engine'.) In a manuscript from 1837 that Babbage did not bother to publish he proposes to use punch cards to store decimal data in a binary code [11]. That is, storage and retrieval of decimal data in a binary code. Dr. Bulow in Germany found in Müller 's collection at Mannheim parts indicating the possible application of the binary notation already by Müller, which is already mentioned in his writings [12].

Electricity: Binary Technology

Hans Christian Ørsted (1777-1851) discovered in April 1820 that a magnetic needle aligns itself perpendicularly to a current-carrying wire. This phenomenon, known as electromagnetism, had been first announced in 1802 by the Italian jurist Gian Domenico Romagnosi but was ignored. It gave impetus to André-Marie Ampère to discover in September 1820 the electromagnet—the magnet that is a coil in which a direct current flows. In 1825, William Sturgeon found that it is possible to increase its intensity many times by introducing a soft-iron core into its coil. Joseph Henry invented in 1828 at Albany New York the electromagnetic switch that causes the opening or closing of an electric circuit, called relay. In 1831 he signaled over 1.6 kilometer circuit, causing an electromagnet to strike a bell.

He predicted in the same year that his method would be used for communications. S. F. B. Morse, who attended at London in 1831 Faraday's and Wheatstone's lectures on electromagnets, discussed the feasibility of the application of the electromagnet for communication. He devised a binary code and later sought a method for its transmission. As a matter of interest, on his return from England Morse went to Henry for advice on how to proceed with his ideas. He got his telegraph patent only by 1838.

Direct-current properties were in use for the production of a dual-state of binary representation by alternating the connections of a direct current source. For example, in the Gauss-Weber electric telegraphs, as well as in the Cooke-Wheatstone one, the binary code was attained by contrary deflections of a magnetic needle. In Göttingen, Germany, by 1833, Carl Friedrich Gauss and Wilhelm Eduard Weber constructed a two wire telegraph line 2.3 kilometer long. The receiver was a heavily constructed bar galvanoscope (a compass-like device for detecting the flow of a current) on which was mounted a mirror. By means of a telescope and a scale placed a few meters away, they observed and recorded the slight tilts of the bar. The code consisted of five successive deflections of the bar, right or left, for each character, more or less after the Cardano's quinary notation. In 1836, in Germany, William Fothergill Cooke devised a three-needle telegraph of six wires. By 1837 in London he formed a partnership with Charles Wheatstone to introduce electric telegraphy (patent July 1837) as an adjunct to visual signals on railways. A codebook based on 20 letters and ten numerals handled the railway's requirements. Because six-wire construction was costly, Cooke and Wheatstone patented in 1845 a successful single-needle instrument, utilizing equal-duration left and right deflections of a needle to denote characters, in a code resembling that of Morse.

The various encoding techniques that the pioneers of the electromagnetic telegraph designed did not apply a fixed number of signals code to produce the symbols or characters. That is, the number of binary signals (electric pulses or punched holes or anything else) were not the same for all symbols or characters. The Gauss-Weber code and that of Charles Babbage were the exceptions. In the early 1850s three Italians, Bonelli, Bolmida and Vicenzia, tried to implement the electromagnet to control the operations and the reading of patterns in the weaving loom [13].

The Perforation as a Means for Storage and Manipulation of Information

Charles Wheatstone (patent in 1858) introduced the punched paper tape as a means for storing and transmission of information by means of the telegraph. However, he used unfixed number of signals code. The use of a fixed code on punched paper tape or cards was introduced already in 1720s, in the silk loom weaving at Lion, France. Enhanced, apparently, in 1728 by the French Jacques de Falcon and Basile Bouchon. Later, in 1745, the ingenious French inventor of automata Jacques de Vaucanson (1709-1782) constructed a totally automatic loom, controlled by a perforated paper roll and a peg cylinder. In 1785, inventor and clergyman Edmund Cartwright (1743-1823) patented the first power loom and set up a cloth factory in Doncaster, England. His power loom was a steam-powered, mechanically-operated. Probably, even earlier, in Austria between 1680 and 1690, a design appeared of an automated draw loom with a binary control by means of wood pegs [14].

Similarly, the idea of the binary code having a fixed pattern composed of six signals was already adopted in the semaphore telegraph (see previous section) by 1795, and in the signaling technique of the English Bishop Murray [15].

Herman Hollerith (1860-1929) provided great stimulus to the application of binary technology and representation for counting and computing, when the perforated card was adopted for use in statistics. Like Babbage, Hollerith applied the punched card in decimal notation in binary code. He did not use the fixed length code pattern, though.

Calculating Devices Lacking the 'Calculating Wheel'

Before reviewing the various means of binary technology developed from the beginning of the twentieth century on, let me note that automatic program-controlled digital calculating machine developed in the period of between 1935 and 1945 relevant to our discussion ceased to use the typical counting wheel elements. The 'wheel' served as the calculating element that characterized all the calculating means since Schickard's 'calculating clock' (1623) onwards [16].

During the 1920s, the application of the binary technology for calculations expanded; it was not confined then just to counting, sorting and tabulating statistical data. The binary technology appeared in mechanical, pneumatic, electromagnetic and electronic components; they were then called ‘switches’. [17] The mechanical switch obtains the dual-state by means of a two-state lever. It represents a switch capable to move into two extreme positions of 45, 90, or 180 degrees, to represent two contrary states.

The master weavers of Lyon, France, used the printed grid paper as a means for designing the silk fabrics patterns. The mathematicians working on the sieve process adopted the grid paper as a matrix in which holes were perforated. The sieve process is a process based on binary notation. It is founded on a very old process used already by the Chinese Sun-Tzu (76 B.C.) to solve problems. The Sun-Tzu procedure was re-discovered and introduced in Europe only by 1856. The first mechanical application of the sieve procedure was performed by the German C. F. Hindenburg and the Austrian Anton Felkel. They developed what is known the stencil method. The stencil is a piece of hard cardboard on which sheets of grid paper were placed. In a predetermined desired pattern holes were perforated in the stencil that were also marked on the girded sheet of paper laying beneath of it. Later on, the stencil was moved carefully in a determined sequence to the end ofthe preplanned area ofthe grid paper, and then the stencil was shifted once more. In this manner, for example, Felkel succeeded in producing a table of divisors of given the natural numbers up to the boundary of ten million [18]. D. H. Lehmer constructed in 1926 an electromagnetic sieve for locating divisors of given natural numbers and by 1932 he completed the construction of his first photo-electric sieve. William Phillips (1936) proposed to use photo-electric cells as switches. The application of photo-electric cells as readers of perforations on cards or sieves based on punching was in abundant use only after 1940.

Electronic Counters

The application of thermionic tubes for counting in the famous counter of Hans Geiger (1908) popularized this technique. W. H. Eccles and F. W. Jordan invented the flip-flop circuit in 1919 by means of a trigger circuit consisting of three thermionic tubes enabling two definite stable states. I. A. Apokin and L. E. Maistrov (1974) claim that in Russia M. A. Bonch Bruevich has invented an electronic trigger circuit in 1918. [19] In the 1930s Wynn-Williams (1931) and others constructed counting means based on vacuum tubes or low pressure filled gas tubes [20].

In the automatic-program-controlled digital calculating machines, the dominant technology of the computing element and other components was binary technology. The term ‘wheel’ is absent in all those designs and will not return any more. A different terminology is applied instead, and that causes some confusion. [21].

Also, the first American electronic 'computer', ENIAC, possessed a computing element called 'vacuum tube rings'; it was a sort of imitation by electronic technology of the calculating teeth wheel element. Therefore, this generalization of the passage to binary technology at that particular period relates more to the change of mind in the application of new means based on that technology rather than the change in perception and in the final breaking-off from the idea of computing by means of the teethed wheel principle. The use of the wheel as a computing element comes a complete end only after 1945.

The Electromagnet and the Punch Equipment

The ability to apply electrical circuits for counting and sorting appeared in the Hollerith's counters and tabulating equipment (1886). Counting is the principal operation of arithmetic: all other operations derive from it: sorting and, consequently, editing, listing and output of tabulated data. Hollerith used the disruption of the flow of the electric current in a conductor as a switching element. In that process he applied the punch card to a multiple electric switches that he created out of tiny springs and pegs. When the pegs passed through the perforated holes of the punched card they closed an electric circuit with mercury found in small concaves located beneath the card. The passage in the tabulating equipment from counting to other arithmetical operations was sluggish and lengthy. Only in the 1930s did IBM and other tabulating equipment firms provide some sort of calculating capacity to their equipment, due to the pressure imposed by customers and special needs like those of the astronomical computing laboratory at Columbia University since 1928. Hollerith constructed an adding apparatus, based on the teeth cogwheel mechanism, in a device developed for the New York Central Railway Station. It was an exception [22]. In 1944, in Germany, the IBM Multiplier model 601 of 1936 was incorporated into an automatic program-controlled digital calculating device, able to calculate numbers of six-by-six or twelve-by-twelve numbers [23].

The calculating element of Harvard Mark I, constructed on IBM punch-equipment, was an imitation of the computing wheel by means of electromagnetic switches technology [24].

The Application of Laws of Electricity in Analogue Calculating Devices

Soon after the results of Ørsted's and Ampère's discoveries were published (1820), the German Johann Schweigger invented the galvanometer. Wheatstone's bridge was invented in 1830. A combination of several resistors connected in a series equals the total sum of all the separate resistors in the circuit: $R=R_1+R_2+R_3+\ldots + R_n$. The formula for a combination of several resistors connected in parallel is a bit more complicated. It has the total sum of the conductors such that the reciprocal value of the sum total equal to the sum of their reciprocal values: $1/ER=1/R_1+1/R_2+\ldots.+1/R_n$.

Lee de Forest, the inventor of the diode in 1906, wrote an article at the late 1890s, proposing to adopt the principle for the adding and multiplying calculating operations [25], utilizing the rules for running electrical currents in circuits by linking resistors in series or in parallel. Since the 1920s, this was utilized in analog devices, such as, for example, the Net Analyzer (see, Chapter 1, Analog Calculating Devices).

Mechanical, Binary Calculating Devices

Before 1935, mechanical calculating devices based on the binary notation were quite rare and hardly known. Only three of the better known will be mentioned here in addition to Zuse's Z1. In 1920, the Spaniard Leonardo Torres y Quevedo demonstrated in Paris a binary electromagnetic calculating device, claiming that he had previously constructed a similar one with mechanical technology. Already in an article 'On Automatics' (1913), he states that he had developed an apparatus that employs binary notation, integrates electromagnets, and exemplifies a universal automatic capacity that may use mechanical technology just as well [26].

The Frenchman Louis Pierre Couffignal (1938) wrote on a binary mechanical calculating device [27].

Already by 1870, the French signal corps officer J.M.E. Baudot (1845-1903) got a patent on a code with a fixed number of 5 signals, enabling the representation of 32 different symbols. Almost in parallel and independently, the American Elisha Grey developed a similar code. By 1874 the Austrian inventor Otto Schaeffler (1838-1928) developed a quadro-printing telegraph, a teleprinter capable of synchronizing simultaneously for delivery four different messages. It was operated by piano keys having 26 alphabetic letters and other characters, transferred into a code of electrical pulses of five binary digits. In 1886, the American Alan Marquand (1853-1924) built a device on electromagnets and logic electric circuits to solve Boolean logic problems [28]. Here for the first time and deliberately the binary technology is utilized for Boolean logic.

Zuse (1936 and 1962) claims that the development of the Z1 is a variant of a purely mechanical device. His aim was to design a mechanical imitation for the electrical relay [29]. In New Zealand in 1913 an automatic (probably binary) mechanical totalizator, was constructed by G. A. Julius [30].

From information available today we may conclude that the development of binary mechanical calculating devices based on purely mechanical switches was a brief and exceptional episode that involved very few people. The design and development of purely binary, mechanical calculating devices is thus an intermediate phase useful for the examination of the feasibility of a certain idea or principle. Despite its simplicity and relatively low cost, the application of binary mechanical technology for calculations did not attract many designers. It caused some technical handicaps in design, inadequate technical reliability and accuracy. The new binary technologies such as the electromagnet and the vacuum tube have provided a wider and more promising scope of operation and rewards for potential inventors.

Electromagnetic Calculating Devices

The development of electromagnetic calculating devices took variegated courses. In Czechoslovakia, in 1923, a patent was issued to B. Weiner for an electromagnetic calculating device [31]. Several designs of counting and calculating devices of the late 1920s and the 1930s rested on electromagnets or the Strowger switch, developed in 1891. These enabled the formation of an array of ten-by-ten states, to represent hundred distinct states. The Strowger relay was a frequent component in automatic telephone exchange [32]. Another control apparatus for the telephone exchange of that period was the crossbar relay that enabled two hundred connections, thus forming a unit for storing up to two hundred numbers [33].

Among the better known calculating devices of the late 1920s constructed with electromagnets, are the totalizators. These were constructed since 1928 onwards for horse-race betting registration. Such a specimen, was constructed by the British Thompson Company in 1930, after a design of an American firm (indicating that the cooperation in calculating equipment between Great Britain and the United States of America originated before

World War II). These totalizators could trace and control in 'real time' all bets set on six horses in a rate of twelve thousand bets per minute; they were small enough to be transferable among various horse racing courses [34]. Similar devices were introduced in department stores for automatic supervision of sales by means of punched tags attached to the products [35].

As our interest lies in calculating devices, I will mention only electromagnetic devices developed for this particular aim. Between 1935 and 1937, Howard Aiken developed two such calculating devices, intended to solve problems with many polynomials [36]. In 1937, Alan Turing developed a binary multiplier [37]. Beavers (1939) gives an account on a small, single-purpose calculating device for summing Fourier series, that contains 16 electro-mechanical counting components [38]. In 1938, at BELL Labs, Stibitz developed a binary adder based on telephone relays, in which he used the bi-quinary notation [39]. J. R. Womersley claims that with the aid of switching engineer G. L. Norfolk he developed during 1937-8 an electromagnetic prototype of Turing's 'Universal Machine' that could perform calculations [40]. At BELL in the early 1930s, E. G. Andrews tried to utilize the standard telephone equipment for calculations [41]. No evidence testifies to the presence before 1930 of a commercial calculating device (excluding tabulating equipment) operating on electromagnets. Ch. Hamann (1932) described a design of such device operating on punched paper tape [42].

In Germany, by 1937, K. Zuse's Z2 utilized for the first time electromagnets for calculations in an automatic program-controlled digital device. Only his patent application (1936) reports that its major part is electromagnets:

> 'The devices and circuits are assembled for most part of relays. For this existing electromagnetic relays can be used, or mechanical coupling an uncoupling devices. Only the circuit diagrams are important. The word 'impulse' can mean a physical pressure, an electrical current or something similar. In the examples cited mostly electrical relays are drawn.' [43].

Lacking financial resources, Zuse turned to construct a mechanical device. Yet, even in his Z4 model of 1944, he still used a mechanical storage.

To conclude. In incorporating electromagnets for calculating, two main and parallel trends existed: one, enhanced by Hollerith, of the perforated paper card or tape, using the decimal notation, mainly for storage, counting and sorting; the other, enhanced by the developers of the automatic telephone exchange, of representing digits by means of the electromagnets themselves; this took diverse directions during the 1920s and the 1930s.

The Utilization of Electronics for Counting and Calculating

In 1908 Geiger introduced the electronic counter. It may be considered as the point of origin of the utilization of electronics for calculation. This provoked the inventors to develop electronic binary counters: the Welsh C. W. Wynn-Williams in the 1930s in Rutherford's lab, the German Schreyer (1938) and the American Mauchly (1936) and Atanasoff (1938). The prominent IBM engineer J. W. Bryce (a member of Aiken's Mark I team) investigated the feasibility of applying electronics to IBM commercial punch equipment [44]. William Phillips claimed that in 1935 he had planned a calculating device based on vacuum tubes [45]. B. O. Williams (1984) lists some twenty American Patent applications presented between 1940 and 1942 for calculating means that were approved before 1946. Most of these patent applications come mainly from commercial firms such as NCR, IBM, and RCA. RCA, for example, had a team that by 1939 succeeded to complete an electronic adder apparatus (device that performs only addition), and by 1942 devised an electronic calculating machine. Norbert Wiener claimed in his *Cybernetics* (1948) that in 1940 he had proposed to Vannevar Bush to develop an electronic program-controlled calculating machine [46].

At the annual meeting of the American Mathematical Society in January 1936 in the opening address, Bush outlined a plan for the design and construction of an electronic, digital, program-controlled calculating device. A project in that direction was sponsored in the late 1930s at MIT, supported by NCR. It was known as the 'Rapid Arithmetical Machine'; it was shelved in 1942 due to war priorities. Some ideas and achievements of this project were handed over to the ENIAC team, not without hindrance.

From mid 1930s, various publications dealt with the possibility of utilizing electronics for counting and for calculations. However, just as in the case of the electromagnetic technology, the electronic binary technology was not always utilized in calculating devices in binary notation [47].

To conclude. (i) Until 1935 there were no electronic calculating devices in use, and no commercial calculating device had been constructed. (ii) Until 1935 the most abundant means based on electronic technology like vacuum tubes or their equals were the various counters applied mainly to physics for counting elementary particles and cosmic rays. (iii) Only after 1935, the utilization of electronic means grew, mainly in research institutes. They utilized for calculations low-pressure gas tubes [48].

The Property of Automatics

So far this presentation focused on two aspects of the introduction of digital devices that were automatic-programed or automatic-program-controlled. One is a survey of the calculating techniques and numerical notations or representations. The other is a description of calculating means between the early seventeenth century (Schickard's) and the 1930s (those available to potential inventors).

Some additional aspects of the introduction of these digital devices concern ideas and tools that could be integrated in digital devices meant to be automatic-programmed or automatic program-controlled. The term 'automatic' refers to systems operating independently or by themselves. This kind of systems may be inanimate or animate. These systems are characterized by the quality of operating by themselves and on their own, according to a preplanned pattern or algorithm designated for them. Our interest focuses on those devices capable to cause a sequence of operations to be executed without human interference and until the completion of the process as desired.

The term 'automatics' was introduced by Leonardo Torres y Quevedo (1913) first as '*automática*' then as '*automatique*'. He did not provide a distinct definition; rather, he gave a description of its qualities:

> 'The name automaton is often given to a machine which imitates the appearance of movements of a man or animal. In general, it concerns a mechanism which carries out certain operations, always the same one, without being subjected to any external influences. There is another type of automaton, which, 'knows', how to maneuver in order to arrive at its target… and thousands of other well-known devices [slot machines] may serve as examples of automata of this second type ...; a manufacturing process is said to have been automated when it can be done entirely by machines. Before going further, it is convenient… to divide the automata into two groups on the basis of whether the circumstances which have to regulate their action do so continuously or whether, on the contrary, they occur abruptly.. This study should, I think, be undertaken in a special chapter of the theory of machines which would be called AUTOMATICS.'

After describing the various 'sense organs, limbs etc.' of the new automaton he added,

> 'Moreover it is essential—being the chief objective of Automatics—that the automata be capable of discernment; that they can at each moment, take account of the information they receive, or even information that they have

> received beforehand, in controlling the required operation. It is necessary that the automata imitate living beings in regulating their actions according to their inputs, and adapt their conduct to changing circumstances.' [Randell, (1982) pp. 89-90].

This is a wish to develop devices that operate independently or that imitate functions of the human body. The concept is old and I will not analyze it here. The mechanical clock, introduced during the 12th century stimulated, apparently, the development of varied apparats and instruments known as 'automata'. Some associate the construction of automata with efforts to imitate the divine creator. Others attribute its development to worship, to ceremonial rituals [49]. Next came music boxes and similar devices. An important step forward towards 'automatics' and later to 'automation' is linked with the silk draw loom. This special loom was operated on by a master weaver and two apprentices. The master recorded in advance on gridded paper the desired fabric pattern to be woven. While weaving, the master followed the marked record and instructed the apprentices which of the thread warps to elevate. This process was laborious, tiresome and costly. The automatic loom governed by perforated paper, tape or cards developed in the period between 1725 and 1804 in Lyon, France, a place that had become the major European center of silk fabric manufacturing. How this passage from the grid paper to punched tape or cards occurred? The passage from weaving, which is a binary technology, to the perforated paper roll or card that stores binary information is exciting and may lead to an additional research [50]. However, once the punched-card controlled loom has been accepted (1805) and got numerous (1820), it was followed by growing and varied application of the punched-hole idea as a means for storage and control of information and mechanisms such as the punching of railway ticket to imprint information. In 1858 the perforated paper tape was incorporated in Wheatstone's automatic printing telegraph, and in parallel in the musical instruments, lathes, lithography, typewriters etc.

The remarkable thing about the Lyon weavers' application of binary technology for control and information storage, as compared to the craftsman's similar construction of music boxes and other automata that utilize the pegged cylinder, is in converting the ordinary loom into a universal, automatic weaving device. The simplicity and flexibility by which it could be operated allowed for the change of patterns at any desired stage of the weaving. The music-box mechanism at its outset was rigid, equipped with a fixed pegged cylinder for a specific tune. It seems that due to the automatic punched-card loom, the idea of the removable pegged cylinder has assimilated to the construction of music boxes in the middle of the 19th century. By then, technologists changed the music boxes to the gramophone pattern (the turntable), with replaceable perforated disk record or pegged drum, enabling a collection of a variety of pieces of music.

The use of perforated paper was a break-through; it was achieved in automata during the 19th century. Till the 19th century, the automated was a tool dedicated to a single purpose, capable of executing a single action or at most a defined number of operations according to a fixed plan imprinted in hardware of the device. From the 19th century onwards, control systems appeared that permit the assignment of a variety of functions without the need to change the hardware, the physical structure of the device: the change is of its operating program—on its software.

An additional control mechanism, typical of the clock, is the governor. It entered the scene at the end of 18th century. In essence, the mechanical clock is a machine that divides the uniform, continuous movement into discreet intervals, the counting of which enables to consider each interval a single units of time [51]. The main task that the clock poses is to split and maintain the movement in constant and uniform speed. Any change in speed of movement of the teeth cogwheel gear mechanism will cause inaccuracies in the rating of the intervals, thus effecting the accuracy of the instrument. Visitor in museums of clock-displays may observe many techniques designed to split the continuous movement and split it to definite and constant time intervals. Hence, any clock, including the water-clock, contained a control mechanism, aimed at obtaining and maintaining what students of mechanics call uniform movement. However, this apparatus could not keep always continuous and constant movement as it did not possess an immediate feedback control mechanism. The adjustment of its movement (its accuracy) was in the hands of one who knew where the regulating mechanism is located.

An automatic system requires a control, a feedback and a communication mechanism. The instrument in charge of automation must maintain direct and continued contact with all other active components of the system. The system has to be able to check that the instructions issued by the control component are followed. In 1786, James Watt introduced in one of his steam engines a regulating mechanism that he called ‘Governor’. It was a feed-back mechanism. It controlled the uniform speed of operation of the engine by responding to steam pressure in the boiler or the pistons. Watt’s term ‘governor’ means the ruler of a system—one that governs its operations. In 1854 James Clerk Maxwell provided a study of the operation of governors. It is but the first example of control. [52] The theory of controls in general is due to Norbert Wiener. His term 'Cybernetics' derives from Greek, meaning 'Pilot or Navigator'; it designates control and communication—in animals and machines alike.

The punched paper gained extensive use in telegraph, once Baudot, in 1874, introduced his five signals fixed code. The synthesis between the digital control, based on the punched paper card or tape, with the binary notation character code, gradually closed the gap between numerical and alphabetic symbols. It made possible to pass and represent by digital notation any existing system of symbols. This became a part of the public domain by 1945. However, the background for it was already previously set, by Leibniz (1697) and later on by Gödel (1931), Post, Church and Turing (1935-1936).

After 1935, the digital control—based on punched tape or on cards—is integrated in the automatic program-controlled digital calculating machines, as well as in analog devices such as the MIT electronic analyzer (1942). Here the transfer of technology from telegraphy is evident. Some of the developers utilized standard telegraph equipment such as teleprinters as controls or as input-output components. The control technique of the perforated paper tape is a sequential control. That is to say, a complex action is split into a number of basic, distinct consequent operations, followed one after the other in a predetermined order.

In 1930, and even before (Torres, 1919), ideas spread for integrating and synchronizing calculating devices with other means, such as typewriters, tabulators and accountancy machines. It represented a fixed sequential or parallel control enabling the execution of several operations simultaneously and in parallel. Here, one operation effects always and at the same time several sub-systems integrated in a communication system.

Another type of control and automatics evolved from the telephone exchange equipment [53]. The connecting board of the manual telephone exchange served as an important component in several of the digital calculating devices such as the 'Bombs' and 'Colossus' in Bletchley Park in England and in Harvard's MARK I in the USA. The connecting board control permits the changing of the routing of the communication cables whenever needed, thus causing a change in the hardware structure. From the plain theoretical point of view, there is not much conceptual difference between the punched paper and the telephone board control. For, it is possible by means of a suitable program to overcome any hindrance that the hardware sets. This is the innovation in Turing's famous paper of 1936, on its utmost emphasis on the economy in hardware through flexibility of software. Later (1945), this resulted in a disagreement between Turing and other members of NPL (National Physical Laboratory) while designing the ACE (Automatic Electronic Engine). That is the gist of the Turing-von Neumann conceptual difference in the design of the computer—minimum hardware versus hardware as compensating for software. A thorough debate on this issue exists in Carpenter and Duran (August 1977), 'The other Turing Machine'. [54]

The reading of instructions and of data in the automatic program-controlled digital calculating machines was achieved by diverse techniques: mechanical, electro-optical, or photo-electric. The instructions code was quite extensive. Zuse adopted a fixed code of eight binary-digits signals punched on a 35 mm exposed photographic film fed by means of a movie projector. The Bletchley Park inventors utilized the fixed five signal binary (Baudot-Murray) code, standard in telegraphy, probably influenced by designers of the Royal Mail who constructed the Bletchley park machines. Aiken, Stibitz, Mauchly and Atanasoff combined control equipment of telegraphy and punched paper tape and standard IBM commercial punch equipment with some modifications.

Storing, Input-Output and Communication Means Utilized in Calculating devices

Finally, this survey turns to storage, input-output and communications means relevant to our story. The means of input-output, being available to most of the developers of automatic program-controlled digital calculating machines, were the punched paper cards or tapes, applying arbitrary numerical notations. In Colossus and the BELL computers, the input and output means were electrical typewriters or teleprinters. To the disposal of the designers were many commercially available alternative punch equipment tools for perforating the paper tapes and cards. Most of the automatic program-controlled digital calculating machines utilized them or some imitations of them. A possible exception is Atanasoff, whose assistant, C. E. Berry was given as part of his MA work the task of designing a very fast input-output apparatus to punch paper cards by electric sparks and to read data by a photo-electric cell.

The term 'storage' is not included in the description of the automatic program-controlled digital calculating machines under discussion. However, in my Introduction I have stated unequivocally that the machine had to possess a storage unit for data and for instructions. An automatic program-controlled system is impossible without the possession of storage for data and for instructions of some sort, to serve as mediating medium for intermediate or final results. In the above presentation the communication means is not mentioned either and was added, during the debate, due to its strong affiliation with the property of automation and control. The communication among the various parts and components rested almost entirely on electrical conductors.

To repeat, since the 19th century, storage techniques of digital information were the punched paper tape and the card. These comprise the mechanical media. At the early 1920s, electromagnetic and electronic storage means, (Eccles-Jordan vacuum tube trigger—by today's definition a flip-flop) or accumulators of information are introduced [55]. Electromagnetic means for latching binary information is the relay. The Strowger switch rests on two electromagnets creating 10X10 array matrix designated for automatic telephone exchange to represent hundred states of communication. [56] In 1906, the decimal telephone dial was developed; it permitted the utilization of the Strowger switch for automatic dialing—connection between subscribers. The standard telephone dial generates ten distinct well graded electrical pulses on the Strowger switch. Moreover, at the beginning of the twentieth century, mechanical registers were equipped with teeth-wheels or a variety of levers. Babbage planned a 'store' for storing one thousand numbers of fifty-three digits each, including their algebraic sign. The Babbage store was supposed to contain more than sixty thousand teeth wheels. Accountancy machines, such as that of NCR-11 of the 1930s, had six registers. L. Comrie discusses the question, how could the standard accountancy machine NCR-11 be utilized for calculations up to sixth difference, as envisaged by Babbage [57]. A common mechanical calculating machine of the 1930s, was equipped with one or two storage registers. Couffignal (1933) comments on a Campos accounting machine as having a storage of one thousand registers. [58] It had an important innovation enabling specifying an index number (index addressing), of corresponding register that either retrieved or stored the number to the accumulator. Moreover, the machine could automatically set a number into two different accumulators, allowing double entry accounting. It enabled the performance of checks by automatically assigning consecutive index numbers to successive operations. [59] Campos (1944) gives an account on a Logabox bookkeeping machine, having a mechanical, numerical index access address storage, having the capacity of two hundred numbers of 13 digits each. There are examples of the application of the machine for harmonic analysis and the solution of simultaneous linear equations [60].

Storage means of considerable capacity of thousands data with speedy storage and retrieval existed up to 1935 in horse batting totalizators, in accounting and book-keeping equipment as well as, in department stores, banks and other commercial places. Most of these were recorded by electromagnets and punched paper.

Logic Properties in Calculating Devices

No conscious application of Boolean algebra or logic for the design of switching circuits or logical circuits for calculating devices in binary technology of before 1938 is known, except for the American Alan Marquand (1853-1924) who built in 1886 an electromagnetic device with electric circuits in order to solve problems of Boolean logic. Even the logical properties of the various switching-means that could be represented and implemented by means of the Boolean algebra were rare before the known dissertation that Claude Shannon has submitted towards a master's degree (1938). [61] In it he showed how circuits could represent symbolic logic, and gave an example of a circuit for the addition of two binary numbers. Yet, one may assume, logicians, engineers or anyone involved with switching and communications could perceive and cope with this, even before a well-defined switching discipline was formulated.

Summary Chapter 2

What then were the outstanding conditions that might have brought about the integration and synthesis of those separate and distinct means discussed here, into automatic program-controlled digital calculating machines? I present as automatic program-controlled digital calculating machines the integration of diverse technologies: calculating elements, control apparatus, communication means, storage components, motive power and input-output devices; what has brought them to integrate into one installation or system to obtain the new concept? The difficulty in answering this question is attributed to the commonly excepted answer of 'when the conditions were ripe.' It is a deterministic answer, borrowed from an evolutionist concept of biology. What makes the 1930s unique from the years that preceded them? Something makes the 1930s outstanding when compared with preceding years, as it was then that the development of automatic program-controlled digital calculating machine took place. There is no single plain answer or argument that may explain the situation, one that may indicate what these conditions could be, one that may bring together and synthesize the distinct components to a single assembly unity, one that is in itself more than just the sum of the individual means, qualities, or performances. The above answer describes an existing state of affairs rather than an explanation of it. In the search for sufficient conditions for this integration we may find some fruitful idea. Vannevar Bush has outlined in 1936 a program for closer cooperation between mathematicians and constructors of calculating devices for the development of automatic program-controlled digital calculating machine. Turing's paper of that very same year (1936) is also an outline of such a program. [62] However, the evidence indicates that most of the constructors of the automatic program-controlled digital calculating machines were not aware at all of these publications. They had no effect whatsoever on the development of these devices, to the exclusion of Turing and Bush themselves, obviously (Part II discusses this in some depth.)

The quest for an explanation to the appearance of these devices then, by dividing the condition to the external and the internal, as is a common practice in social science studies, does not contribute much to clarify the complexity of the terms as 'when the conditions were ripe'. Is it possible that a solution can be obtained by relating events to two opposing or split levels of causes, such as the division between 'micro' and 'macro'? Will the division of Yehuda Elkana of the philosophy of ideas to two tiers of thinking offer any help? He offered two such divisions, one between the realistic and the relativistic, and one between normal reasoning and the meta-level of our reasoning. Claiming that we can act and think simultaneously on both levels, combining them with diverse images of knowledge, he hoped to explain acts of integration of thought. I have no opinion to that. But I reckon that answers of the sort of 'when conditions ripe' do not contribute much to the understanding the phenomenon of the introduction of the automatic program-controlled digital calculating machine in the second half of the 1930s. The answer 'conditions were ripe', does not provide an explanation of the fact that the synthesis of the 1930s occurred particularly in Germany, Britain and the USA, and what was so propitious in these countries but not France, for example. Nor can we pin it down on the regime and the economic and social conditions in the period of 1935-1945. In Germany those differed from the ones in the USA and the UK much more than the ones in France.

Regarding the devices discussed here, a synthesis was made of binary tools and techniques, in abandonment of the traditional counting wheel. Aiken's MARK I and ENIAC somewhat exceptional on this, as in them the calculating element is an electromagnetic and electronic tube that imitate the counting wheel. In the newly designed automatic program-controlled digital calculating machines, a synthesis was performed under one roof of sequential control, teleprinter-telegraph communication, calculating and storage components based unconsciously on Boolean logic, integrated with iterative and difference calculating techniques, all of which were generally known for quite some time. In the Summary of Part I below I will provide additional alternative answers, coping with the occurrences that took place in the 1930s and with their influence on the development of the automatic program-controlled digital calculating machines.

PART I SUMMARY

This part has provided the historical background. The question set was this. What of those devices of before 1935 has been incorporated as components in the computer and why they are not computers? The discussion about this question focused on examining tools, components, techniques and ideas of before 1935, present in calculating machines, calculating instruments and other devices that could be integrated in the automatic program-controlled digital calculating machines.

By conducting a comprehensive list of pre-1935 tools, techniques and ideas, I tried to show that the automatic program-controlled digital calculating machines were developed independently of and in indifference to all the past calculating devices and that the linear approach in the history of the computer does not reflect what happened during the period 1935-1945.

This presentation concerns digital calculating devices, because many scholars consider them the origin of the automatic program-controlled digital calculating machines. What is essential for the digital automatic program-controlled devices yet is missing from the pre-1935 calculating devices were the changeable program and the control mechanism. The inability to change the program of the device and to provide it with the capacity to respond to a purpose. Moreover, these devices did not possess a communication component that would allow them to maneuver between the various components and particularly between the storage and retrieval of data and the results. Still, the pre-1935 calculating devices did incorporate three of the components included in the characterization of the automatic program-controlled digital calculating machines. These are the input-output components and the calculating element. Some calculating devices, such as calculating machines and cash registers, contained tools for storage, even though in a limited fashion, in the punch equipment; the storage capacity was extended on punched cards.

Other questions arise. What were then those unique conditions in the 1930s that enabled the synthesis and integration of the discreet means and ideas to design the entirely different item that I term ‘automatic program-controlled digital calculating machine’? What made it possible to synthesize various technologies of calculating elements, control mechanisms, communication components, storage means, driving and motive force apparats, and output and input components, into the new concept of the 'automatic program-controlled digital calculating machine'? Some answers to these two questions will be discussed here. Before answering them, I will refer to the question posed at the beginning of this part: What was in those calculating devices of before 1935 that made them components of the computer, and why, nonetheless, they could not be considered computers?

The answer of the first question is this. The pre-1935 calculating devices incorporate parts of the most vital components needed for rendering a device a computer or even merely an automatic program-controlled digital calculating machine. Yet they lacked the program-control property. Thus, they lacked the general-purpose capacity that is a precondition for counting as computers. The pre-1935 calculating means possess some properties of the computer, namely, the ability to calculate. The computer is a symbol crunching or manipulating machine that includes data and instructions. Nevertheless, the calculating devices described here contained certain components that served as ingredients in the automatic program-controlled digital calculating machines. The input-output devices were taken from the punch equipment. Existing components, techniques and ideas of direct multiplication by means of multiplication-tables and of trigonometric functions and other mathematical and functions were also absorbed into computers proper.

The answer to the second question is this. Even the most advanced pre-1935 calculating devices are not computers since they are applicable to a limited and very narrow scope of solutions, due to limitations imposed on them by their hardware structures. As single purpose devices, they lack the general purpose quality and are not capable of performing any algorithm. The vital want of the property of general purpose and universality (capacity to imitate any type of machine), deprives them of the ability to serve as computers.

In spite of the fact that abundant, diverse pre-1935 techniques, ideas and components that have been incorporated and synthesized in automatic program-controlled digital calculating machines, nonetheless, the overall result of these syntheses does not imply any continuity between events that took place before and after 1935. The presence of a certain component in a calculating device does not render it a computer. Just as the boiling kettle emitting steam and pushing up its cover is not the source of the steam engine, just as the spear and the bow-and-arrow are not the sources of the cannon, the rocket or the aircraft, so the antecedents to the computer are not its source. The confusion on this matter derives from seeing the growth of technology as an evolutionary process, as technological Darwinism. Not so: the computer is not the result of mutations of pre-1935 calculating devices.

PART II

THE PERIOD 1935-1945

CHAPTER THREE

THE INDIVIDUAL AND COLLECTIVE BIOGRAPHICAL PROFILE OF THE DEVELOPERS OF THE PERIOD 1935-1945

Introduction

This part contains two chapters: Chapter 3 deals with the individual biographical profile of the developers of automatic program-controlled digital calculating machines that acted in Germany, the USA and the UK in the period 1935-1945, focusing upon the question: what was the interdependence or relationship between the education and deeds of the developers and the devices being developed? Chapter 4 focuses upon the questions of why they did what they did, and what the relationship was between their education, deeds and work and the formalization of mathematical logic and the introduction of the digital computer.

I will use the example of the weaving loom, in which the output is the fabric, while the transferred information *via* the loom's medium is the decorative woven design of the fabric, the pattern. This distinction, between the imprinted information in the hardware medium (the lengthwise and crosswise threads of the woven fabric) and the product, or output, is typical for the designers of automatic looms that used punched paper tape or card for storing the information of the designed fabric pattern. In like manner, the craftsmen of music boxes were also assisted by the distinction, between imprinted information in the hardware medium and the output, in utilizing the pegged cylinder for the storage and retrieval of melodic information. The developers of automatic program-controlled digital calculating machines also applied the various binary technologies (punched card/tape and the relay or switch) to represent, store, retrieve and process digital data and instructions. In these devices, the hard copy output on paper, card or on the monitor (CTR) expresses the fabric (the medium) on which the pattern is imprinted, while the individual results represent those final decorations of the fabric. As Ada Lovelace has put it, on the qualities of Babbage's

Analytical Engine (in a translation of and remarks to L. Menabrea's article from October 1842):

> 'In studying the action of the Analytical Engine, we find that the peculiar and independent nature of the considerations which in all mathematical analysis belong to 'operations', as distinguished from 'the objects operated upon' and from the 'results' of the operations performed upon those objects, is very strikingly defined and separated... by the word 'operation', we mean 'any process which alters the mutual relation of two or more things', be this relation of what kind it may' [1].

She added,

> 'We may say most aptly that the Analytical Engine 'weaves algebraic patterns' just as the Jacquard loom weaves flowers and leaves' [2].

The educational background of the developers of the automatic program-controlled digital calculating machines in the period 1935-1945 was in engineering, physics, or mathematics, or a synthesis of all three. Most were graduates of technical higher education schools and had some practical and theoretical knowledge in mathematics, electricity and electronics, which then was not yet a separate or independent discipline. Before the 1930s, the term 'electronics' belonged to a sub-branch of electrochemistry concerned with the behavior of electrons.

The developers possessed a very broad formal academic education and most of them were PhDs or PhD students. They were a different kind of inventor from those known hitherto, such as Watt, Faraday, Edison or even Boole, who were self-educated from outside academia. This was a young group of academics, mostly in their twenties or at least below thirty-five, coming from different spheres of interest and activity, burdened with analytic problems that demanded huge amounts of complex calculations. However, the development of the automatic program-controlled digital calculating machines by these developers did not result directly from unique or specific calculating needs of that period. On the contrary, for specific needs specific solutions had been provided. Most of the common calculating devices in the 1930s sufficed for the calculating needs of that era, whether in engineering or in other professions. In most cases even the standard slide-rule provided solutions of sufficient accuracy. Moreover, the analog devices until 1945 (the time of the operation of ENIAC) were at that time faster than the automatic program-controlled digital calculating machines of concern to the present work. Hence, even the factor of speed cannot be attributed with influence or necessity to their development. Furthermore, the claim is no more than sheer vanity that the need in the 1930s for more complex calculations brought about the development of these devices.

From the outset and until the crystallization of the idea of the device and the examination of its feasibility, the developers acted independently and in isolation. Later on, mathematicians or physicists whom the idea fascinated joined forces with an expert in electronics, electricity or other form of communications. This was the case of Zuse and Schreyer; George Stibitz and S. B. Williams; Mauchly and Eckert; Atanasoff and Berry; Aiken and the IBM team, on its engineers and technicians; and Turing and the British Post Office and other communications experts such as the TRE (Telecommunication Research Establishment) involved in the development of electronic technology such as the radar.

The feasibility of utilizing vacuum tubes for counting and storage needs, the idea on which ENIAC (the electronic computer built at the University of Pennsylvania) rested, was tested by the use of the two electronic accumulators test, carried out at the end of June 1944. This test served as a decision junction to determine how to proceed with the development of the project. In spite of adopting the binary technology for design and construction, the ENIAC developers used decimal representation, in which elements of the electronic vacuum tube rings imitated the calculating wheel.

'The invention of the computer' is an issue so open to dispute because telling exactly who invented what is so confusing as people implemented and integrated a wide diversity of ideas and technologies throughout the course of its development. Therefore, it may preferably be more accurate to discuss the development of the computer rather than its invention. Only after the developers crystallized and designed their ideas did they begin looking for suitable information produced by others. Patterns of the implementation of information once it was acquired or required, varied greatly.

It is possible to trace a certain common background among the various developers. In the 1930s, there was a greater interface between the domains of physics, engineering and mathematics and less compartmentalization amongst related disciplines. Cross-disciplinary work was met without today's routine resistance. Even such claims as 'the shadows of approaching war or the war itself' as possible explanations for the introduction of the automatic program-controlled digital calculating machines are shaky and controversial. Some developments did indeed appear due to the war, but others were plainly suspended by the war (for example, Atanasoff, Schreyer, IPM and RAM of MIT).

Some scholars—such as W. F. Aspray; see his doctorate work (1980)—are of the opinion that those developments derived from David Hilbert's program (from 1900 to 1928), which was the attempt to formalize the whole of mathematics and present it in a few basic axioms. In salient truth, Babbage (1834) and Ludgate (1909) conceived, designed and strove to develop analytical engines that contained most of the components and ideas of the automatic program-controlled digital calculating machines well before Hilbert's program of 1900. The same holds for the *Principia Mathematica* of 1910-13 of Alfred North Whitehead and Bertrand Russell. It is plausible that Babbage and, before him Leibniz and later the developers of the automatic program-controlled digital calculating machines in the period of 1935-1945 treated information and data as commodities and as concrete resources. They understood that in their machines, the reference to numbers deviated beyond the traditional treatment of numbers as abstract entities as has been so commonly the case within the conventional means of calculation. Yet this awareness that mathematics is a language with its own syntax had already been exhibited by 17th century scholars. Leibniz (1679-1714) even went beyond this, arguing that information in general, and not just the mathematical entities, could be expressed in a formal universal language based on a digital syntax (binary), a concept fully worked out anew and independently in the 19th century by George Boole (1854). The view that it is possible to manipulate information, in its widest sense, does derive from Hilbert's program as well as from the works of other mathematical logicians such as Frege, Russell, Gödel, Church, Post and Turing. But, as to the extent of the influence of mathematical logic on the developers of these devices here under discussion, it is at best the most controversial issue. My discussion of Answer 5 in Part X below focuses on this issue and shows that there was no such connection between the works published in the area of mathematical logic and the introduction of these devices. Nevertheless, the matter is re-examined in Chapter 3 for each of the inventors independently in order to explore the invention phase itself better. To wit: first I will provide biographical evidence about this group of developers in Germany, the USA and the UK who, during the years 1935-1945, were involved directly in the development of automatic program-controlled digital calculating machines. Then I will investigate whether there was any collective program or influence on which these developers could rely, and why the events occurred as they did, exactly so, during the years 1935-1945 and in those countries. Finally, conclusions will be deduced from the biographical information as to the collective portrait of this group.

Biographical Sources

My presentation of the biographies will begin with the German developers, because the origins of the computer in Germany are less complex and controversial. The evidence here is derived in the main from my prolonged personal discussion on 19th September 1986 with Konrad Zuse and, to a lesser extent, other sources.

Zuse, in contrast to other developers under discussion, is the only developer who has written a personal biography [3]. Later, my biographical survey moves to the USA, where during the period under discussion five developers acted in parallel. In the USA, unlike the events in Germany, the history of the computer remains extremely controversial, particularly anything which had to do with the priorities, honor and patent rights of those electronic automatic program-controlled digital calculating machines. For some reason, in the USA, the developers of these calculating devices have no written autobiographies, and to a certain extent they caused, maybe intentionally, indistinct ambiguities regarding their early past before these developments occurred. Unfortunately, two of these developers, Aiken and Mauchly, have already passed away, and I failed to obtain an interview with Eckert, though I had a telephone conversation with him on a certain issue concerning ENIAC; however, Stibitz and I did have a long discussion on 17th October 1986. Some additional biographies are now available, including *The First Electronic Computer: The Atanasoff Story* of 1989, written by Alice and Arthur Burks. Yet, they are in dispute with Mauchly and Eckert, As Burks demands to be recognized as a co-inventor of ENIAC. A second book, *Howard Aiken: Portrait of a Computer Pioneer*, edited by Professor I. B. Cohen, finally appeared in 1999. It is doubtful whether such a collection can be considered biographical.

As for the UK, the matter is still more complicated. Here the subject matter relates to a classified project still under the Official Secrets Act, of which almost nothing has been published officially and is kept from the prying eyes of scholars until 2006, when a part of the material in question was declassified. Professor B. Randell has published earlier several papers on it; he had some interviews with the people on the project. A special issue of the *Annals of the History of Computing* was devoted to the Colossus. Yet the British project resulted from teamwork, and the specific contribution of each of the members of the team was not cleared there. In contrast to Germany and the USA, in the UK the issue of priority, honor and royalties has never been a public issue or matter of controversy. If there was such a dispute, apparently it has been conducted discretely between English gentlemen. In the 2006 volume that appeared after the veil of secrecy was lifted Peter Hilton speaks (p. 196) of ‘real camaraderie’ and of ‘happy atmosphere’. I have chosen to portray several people whose contribution in the UK I consider crucial to the appearance of calculating devices, who are not necessarily those that claim to have been ‘computer pioneers’. In a discussion held on 14th March 1987 with Professor B. Randell of the University of Newcastle upon Tyne, who to my mind is one of the most authoritative scholars on the history of the computer in general and in the UK in particular, it became clear to me that the biographical information about the UK developers of automatic program-controlled digital calculating machines is very vague and indistinct. (For details, see the following section related to the UK.)

Finally, I have to say a few words on the historiography of computers. The most noteworthy point is that the developers did not keep personal diaries or records as events unfolded. At firms like IBM and Bell the regulations prevented employees from keeping such personal diaries or records related to their inventions. Most of the documentation and recording was carried out in formal documents and reports, being in essence technical or describing the state of affairs or the advancement of the project. Only by the end of the 1940s did the developers begin to pay any attention to their deeds from a historical perspective, when problems arose with priorities, patent rights, royalties and honor. Only after World War II did development accelerate seriously in the USA and the UK, and it remained at a standstill in Germany until the 1950s, when Zuse reinvigorated their development. Actually, he had briefly suspended their work. After the war, new and diverse components and ideas were implemented, deriving from new binary technologies such as the transistor, or even pre-existing technologies such as the magnetic drum or tape. Every improvement or event like this was considered as a breakthrough, innovative or ‘pioneering’. In the period after 1946 many developers gained renown as ‘computer pioneers’, for example Professor M. V. Wilkes, with whom I discussed the issue at Cambridge on September 30, 1986, and who was appointed after the war as the director of the Cambridge Mathematical Laboratory. In August 1946 he participated at the Moore School for Electrical Engineering (University of Pennsylvania) in the final part of a special course provided to a group of 28 top, specially selected students from the USA and the UK on ‘Theory and Techniques for the Design of Electronic Digital Computers’. On his return to the UK, he designed with his colleagues at Cambridge the Electronic Delay Storage Automatic Calculator (EDSAC), known as the first electronic computer with internal storage, designed according to the ‘First Draft’ of von Neumann (see Appendix B). In the EDSAC, binary notation, sequential control and acoustic storage based on mercury delay lines (an idea of the ENIAC team member P. Eckert) were implemented successfully. The EDSAC was publicly unveiled during a conference held at Cambridge for its inauguration between June 22 and 25, 1949. Since then, Wilkes has turned out to be one of the most prolific publishers and participants in the history of computers. One of his last publications was his autobiographical *Memoir of a Computer Pioneer*, no less! Make no mistake: the title speaks for itself, particularly if we consider it in light of his deep interest in Babbage, as expressed in articles entitled: 'How Babbage's Dream Came True' and 'Babbage as a Computer Pioneer'. Many desire to bear the title of 'computer pioneer', as indicated by the long list of publications incorporating the appellation 'computer pioneer' [4].

The introduction of the digital computer is one of the most important events of the modem era. That people of the era, past and present, have been conscious of the drastic change and the revolution that these devices have created, brings a great deal of ego into play, and decisively so. Therefore, it is little wonder that Wilkes, and others who later took some part in the development of the computer, are heralded and recognized as pioneers in the history of computers, even though their contribution might only have been an improvement that enabled the realization of a certain idea (in Wilkes' case, being the first to implement the stored program concept and the mercury delay line).

Another resource is oral history, or tape-recorded documentation. A wide scale project was undertaken during the 1970s to tape-record the people involved in the various projects, where these automatic program-controlled digital calculating machines were developed. Gatherings and conferences have also been held to commemorate events connected with the history of the computer, in which memories were told by the different developers [5]. The severe limitation of those interviews and oral history projects, such as those carried out by Henry S. Tropp of the Smithsonian Institution, Washington D.C. and by Christopher Riche Evans of the Science Museum of London, is that the questions asked are of a very general nature and the answers given have been even more general. Generally speaking, the interviewer 'lobbed softballs', refraining from asking incisive or clarifying questions to explicate biographical or other unique details. This was probably due to an interest in keeping the continuity of the narration or being polite to the interviewee by not interrupting them during the interview, even though he did not answer the questions asked. The interviews focused upon commonly known disputes. This documentation deals with events that occurred after the development of these devices and not with the motivations and ideas that were behind their development. Therefore, this documentation is extremely poor with regard to events relevant to the discussion at hand [6]. In such interviews, the interviewer is obliged to see that the interviewee answers the questions presented to him. Obviously, the interviewee has the privilege to refuse to answer any of the questions, for reasons kept to himself, but in this case it is the duty of the interviewer to confirm it explicitly and it must be expressed in the recorded text. These interviewees have got considerable experience in this type of interview, chiefly made by press reporters. Normally they are asked to give an account on the moment of 'revelation' or prophesize on the hidden virtues of their discovery. The new devices excite the imagination of the reporters, captivated in 'eureka' descriptions taken from popular history books, such as those of Archimedes in the bath which inspired him to discover the law of buoyancy, Newton's falling apple and the law of gravity, and Kekulé's dream that has led to his discovery of the benzene ring bond in organic chemistry. These types of accounts have been readily absorbable in the media and popular magazines and were accepted sympathetically by the wider public. It is fascinating to see how, during their interview, the interviewee draws back persistently to such occurrences. The interviewee intentionally or unintentionally evades questions concerning details of his life, because he does not ascribe significance to them, possibly because most of the interviewers were so inexpert on the subject of their interviewee's background, and never did their homework. Besides this, the meeting with the developer served as an occasion to gather data and information, not to verify particular points on specific issues.

In interviews I adopted Professor Agassi's method that he used in his seminars. It was introduced to the interviewees and agreed upon at the outset to be the procedure of the interview without any difficulty or objection. I explained to the interviewee in advance that the 'important' and 'great' events and information are already well known to me and others, and that their place in history as computer pioneers is secure. Therefore, for reasons of economy of time and effectiveness of discussion, at the very moment that they slide towards known issues or in case they do not answer the question, I would cut them off by raising my hand or calling out: 'Stop!' I emphasized that my interest is precisely in the 'futile' and 'trivial' matters that usually people gloss over, assuming them to be unimportant and plunging headlong to the celebrated 'eureka' moments. I must point out that this procedure proved effective beyond my expectations. As a testament to this style of journalistic interrogation, we may find a comment made in the opening paragraph of a very long and dense letter sent by Professor Atanasoff to me on 18th December 1986:

> 'I am 83, seemingly very busy, have little time for what you ask but I have interest in your approach, and will write a little. I have been lucky and will write what I think is important.'

This was a reply to my letter of 1st December 1986, in which I asked him to write some biographical details about himself. I stressed that I was familiar with all the events that happened after 1938 and that therefore what I would like him to write was:

> 'If possible, write it as a story to one of your grandchildren at the age of 14-16, in which you convey your memoir up to 1938 when you got the idea of constructing an electronic computer. You will notice that the natural trend will be to skip the early period in which I am interested and junp always to the era 1938-1942. I am interested in the events that happened before this time. The more details you provide the better, even if you think they are unimportant.'

Moreover, in order to omit the well-known accounts and controversies I indicated:

> 'I do not have any doubt of your being one of the computer pioneers and that is how I describe you in my work.'

Atanasoff responded straightforwardly to this in the third sentence of his letter:

> 'Correction: I am 'the' not 'one of the' pioneers. I changed computing from Babbage to the modern structure. My machine was more like the modern than ENIAC although Burks proves I invented ENIAC.'

This phenomenon, so sharply reflected in the last few paragraphs, indicates such fierce struggles over priority and primacy rights and the recognition of being a 'pioneer' or 'co-inventor' of the invention of this or that device, demonstrating the historiographical importance of sheer unmitigated ego. When I proposed to Zuse that he publish a certain document (from January 1936) from his personal archive collection, giving an account of the advantages of the binary notation in mechanized computing as against other numerical representations, he complained to me that 'the Americans think that the computer is an American invention'.

In a discussion held with Alice and Arthur Burks in Ann Arbor on October 11, 1986, I raised the question: 'Why do they write so much about Atanasoff and why is what he contributed so important to the history of computing? It is evident today that even without considering the ENIAC and the Atanasoff device, other such electronic devices have been developed, for example the

Colossus.' They replied, 'he is important because he was the first, and therefore he deserves to be entitled with the primogeniture right, Mauchly has taken his idea from him.'

However indirectly, they were trying to secure their own rights as computer pioneers. If Mauchly and Eckert were not those that invented the ENIAC, but were just developers of a concrete idea of somebody else—that of Atanasoff—then the claims of the Burks' (and their colleagues) on the ENIAC patent are equal to those of Mauchly and Eckert.

Now, concluding this digression concerning oral documentation, let me resume the discussion of the independent biographies of the developers, beginning in Germany.

Germany

In Germany the presentation focuses upon two developers, of whom Konrad Zuse is the dominant one, while the other, Helmut Schreyer, is of lesser importance. At the outset Zuse and Schreyer acted together in Berlin (1934-1941), and later carried on separately and in parallel until the war's end. There was impressive activity in this *milieu* of automatic program-controlled digital calculating machines at Darmstadt in the Institute for Practical Mathematics (IPM) before and during World War II led by Alwin Walther and the brothers G. and G. Dirks, but that is outside the scope of our discussion.

Konrad Zuse

Zuse was born on 22nd June 1910 in Berlin, where his father worked as a postal clerk. After his birth, the Zuse family moved to Braunsberg in Eastern Prussia, now the Polish town of Braiewo, between Gdansk and Königsberg, where he spent his childhood. He studied in a primary school of conservative tradition which stressed Latin and not vocational studies. After a few years in that school he transferred to a school at Hoyerswerda, in Silesia near Dresden, whose curriculum was more progressive.

Zuse possessed two major qualities: that of an artist, and that of an inventor. The distinct gulf between these two qualities is bridged by imagination. When he busied himself with painting or acting he did not engage himself with invention and *vice versa*. From the age of two he displayed a proclivity to drawing and painting. In his boyhood he turned to inventions and was attracted particularly to the construction of coin-operated slot machine automata. Slot machines had started to appear sometime in 1888; the automata for selling and dispensing cigarettes had been introduced in the 1920s. Zuse designed a prototype of an automatic machine that did not exist yet, but he did not bother to apply for a patent for it. It could sell several products simultaneously, distinguish between different coins, and give the exact change; it was only by 1928 that such machines were eventually developed. Zuse was very much influenced by traffic lights in Berlin and designed a new city model, which he named 'Metropolis', in which he strove to solve problems of quality of life, and especially the problems of motorcar traffic. He was deeply impressed by Fritz Lang's movie *Metropolis* (the manuscript was written by Lang's ex-wife Thea von Harbou), the contemporary classic cinematic science-fiction social-criticism produced in 1929. As part of his design, Zuse proposed to direct traffic into cloverleaf formations. It may appear that the characterization of a mental compartmentalization between art and invention in the mind of Zuse is somehow refuted here, since the planning of the city and the cloverleaf formation exhibit a synthesis of both. At that time, Zuse also tried to develop a photo apparatus, known today as the Instamatic. It develops pictures in a matter of minutes. He also tried to develop an elliptical movie projector so that every spectator would be able to see the movie undisturbed by any other observer from any place in the cinema.

Between 1928 and 1933, Zuse studied at the *Technische Hochschule* Berlin (now the *Technische Universität* of Berlin). The German technical higher education schools were recognized as academic institutions during the 1870s. Between the universities and the technical higher education schools was a distinct and strict division of duties. The technical higher education schools were in charge of training and graduating qualified engineers, while the universities prepared for other scientific and academic professions.

During his first years of study, Zuse had some difficulty deciding which vocation to choose. At the outset he studied mechanical engineering, but then transferred to architecture because he viewed it as a synthesis between painting and engineering. He also studied acting and performed in amateur theater. Subsequently, he decided to study construction engineering. Documents of the period of his study show that he did not show an outstanding merit in mathematics or calculations. In those days the study of mathematics emphasized practical and applied mathematics. For him mathematics was a means to calculate the constructions of structures. The main objective was the design of a construction and not calculation as such. Yet only then did the problem of calculations begin to trouble him, because the static calculations he was asked to perform as a student were so tedious and tiresome. The calculation of loads and stress, etc. demanded a quick analysis of systems of simultaneous equations with many unknowns. The theory of carrying out such an analysis was well known back then and appeared in the textbooks of the 1930s. Zuse decided to mechanize static calculations. 'I was frightened by any calculating mechanism and therefore I preferred the slide rule.' Once Zuse 'came up' with the idea of performing the calculations automatically, he proceeded by trial and error. At the outset he gave a graphic description of the process of automatic calculation. Later he searched for all the patents available on the issue of calculations and examined them in the German patent office (then in Berlin, now in Munich). There was the approved patent of R. L. A. Valtat (1936) based on binary notation calculations [7]. Zuse claimed later on that back then no binary relay calculating device existed.

During his studies, Zuse also specialized in mechanics and technical drawing but studied very little electricity, much less electronics. Of calculating machines he knew nothing, and he did not use any during his studies. He studied symbolic logic or the theory of groups, despite the fact that in the Germany of the 1930s Göttingen was still the world center in the field, setting the logical foundations for mathematics. In 1932 Zuse became even more interested in automatic calculations, developing by himself a logic documenting technique that he dubbed 'conditioned combinatorics'. In a letter to his previous teacher, Professor Felix Naumann, Zuse describes the logic he worked out. In his reply, Naumann argued that Zuse has discovered independently the propositional calculus. Naumann recommended to Zuse that he read the book of Hilbert and Ackermann on it [8]. Zuse had already tracked down that very book, and was disappointed when he did not find there what he had been looking for. He became acquainted with the works of Gödel, Church, Post and Turing only after the war. It seems that Heinrich Scholz, a professor of mathematical logic, was the only one in Germany who was aware of Turing's work during the years of 1936-1944. He intended to publish it in German in an encyclopedia of mathematics. Scholz visited Zuse's workshop in 1944 on the invitation of one of his former students, Hans Lohmeyen, and it was only then that Zuse learned from Scholz about Turing's work.

Zuse was not aware of Babbage and his work. He learned of Babbage for the first time when applying for a patent in the USA, which was, according to my source, not before 1937. Ceruzzi claims it was not before 1939 [9]. Evidently all of Zuse's activities were undertaken in complete ignorance of what was happening contemporaneously in the USA and the UK. Indeed, he had seen a picture of Aiken's Mark I only in 1943, Hence, it could not have affected his own work earlier [10]. Zuse never left Germany to go abroad until 1946, and he did not know any English.

Zuse points out the strong influence of his friend Schreyer on the design of the electro-magnetic calculating unit and the construction of logic elements by means of radio tubes to represent the logic states of ‘not’, ‘and’ and ‘or’. But back then these states had not been so named. The first patent on such logic gates had been issued in the USA by 1941. Zuse states that the key to practically all the calculations derived from combinations of this logic. However, such claims are in his later writings; there is no evidence of this in his early writings. There is no doubt as to the general truth of Zuse’s claim, yet it seems to me that this view from hindsight is anachronistic.

Zuse graduated as a construction engineer in 1935 from Charlottenburg *Technische Hochschule*. In 1934, he started to work at *Henschel Flugzeugwerke A. G.* There, at the age of 24, he began independently to develop an automatic program-controlled digital calculating machine that he claims was just to avoid the wearing and repetitive calculations of the strength of materials of static or dynamic bodies. First he thought in terms of solving the problem by means of a two dimensional matrix by extracting numerical data from a paper form, on which the data were to be compiled in binary notation by means of an apparatus moving lengthwise and crosswise within a two dimensional coordinate system. This apparatus was meant to convey the binary data in the following formats: data set one beneath the other are to be added or subtracted, and data aligned one next to the other have to be multiplied or divided. What was left was to determine the ‘conveyance of data’ (algorithm or procedure) for the various formulae and their storage at a proper location of the matrix, namely, the solution of the determinants of several linear algebraic equations.

Is it possible that we see here the influence of the flyover sequence in Fritz Lang’s *Metropolis*?

As the other students did, Zuse studied how to perform static and other calculations according to a computing format, the *‘Rechnenplan’*. But the main device by which these calculations were performed was still the slide rule. Calculating machines were in those days still a precious commodity.

In January 1936, Zuse wrote a memorandum that he kept in his house archive. It offers arguments and considerations for the advantages of the binary notation are put forth, pointing out how easily it could be utilized by means of relays for calculations, as compared with the decimal notation.

This is one of the earliest works on the issue of the interesting transformation made from abstract logic statements into a concrete physical body for practical calculations. Before the moment Zuse 'ascended' to the idea of binary notation as a means for carrying out calculations and their storage, he had searched for any available relevant source on it, theoretical and practical. He asked his peers to trace the writings of Leibniz on binary logic notation and calculations in Berlin libraries.

In 1935 Zuse gave up his job at Henschel in order to devote himself completely to the practical development of his idea of the calculating machine. On April 11, 1936, he applied for a German patent for a 'Method for Automatic Execution of Calculations by means of Calculating Machine' [11]. By the year's end, at his parents' house in Berlin, he started to develop the first practical prototype of a mechanical, binary notation calculating device in order to check the feasibility of his idea. He called the device 'Z1'; he completed it by 1938. (It was previously called V1—*Versuchsmodel* (research model)—and changed the name after the war to prevent confusion with the V-1 rocket.) By 1939 he got a small grant from a calculating machine manufacturer, and converted the mechanical calculating unit of the Z1 into an electro-magnetic unit, which was much more reliable. This improved model he named 'Z2'. He claims that his absolute ignorance in calculating devices led him in a direction differing from anything known before. The calculating machine manufacturer, Dr. K. Pannke, who provided the grant, asked Zuse: 'What is the principle of carrying out multiplication in the invented machine, repeating adding or a fixed multiplying table?' Zuse replied, 'In my machine it does not have any meaning', Pannke answered, 'Since Hamann, there has been nothing to innovate in calculating machines!' [12]. This typical response, so customary among professionals and experts, 'there is nothing new that can be invented', appears in many other examples taken as a personal challenge to an aspiring inventor.

In 1941, Zuse constructed the Z3 for the German Aviation Research Establishment, the *Deutsche Versuchsanstalt für Luftfahrt*. It was a digital, electro-magnetic automatic program-controlled multi-purpose calculating device, apparently the first of its kind in the whole world.

By 1943, Zuse had the luxury of renewing his studies as doctoral student. His dissertation title is, 'Statements of a Theory of General Computing Especially with Regard to the Calculus of Prepositions and their Application to the Relay Circuits.' Interestingly, the dissertation was rejected because it dealt with logic switching; after the war he was granted a PhD degree for his practical work. His dissertation was written under the guidance of Alwin Walther of Darmstadt, possibly the greatest authority at the time in Germany in calculating devices and one of its better-known designers and developers before, during and after the War. In 1928, at Darmstadt Technical Higher Education School, Walther founded the Institute for Practical Mathematics (IPM), where digital and analog calculating devices were developed. Two IPM members examined Zuse's Z3 in December 1942.

Zuse had no experience in electricity or practical electronics, although the physics courses that he had attended equipped him with some basic knowledge in electricity and electro-magnetism. Only under Schreyer's influence did he become aware of electro-magnets and vacuum tubes. Zuse used not only electro-magnets, however, due to their high costs and size larger than that of mechanical relays. In all his drawings he used the symbols for switches as commonly applied in electricity. Only after difficulties arose with the functioning of the mechanical calculating unit did Zuse replace them in the Z2 calculating unit with more electro-magnets that he acquired second-hand. At the end of the War, in 1945, lacking the facilities and resources to carry on the practical development and construction of such devices, Zuse developed a theory for programming language: *'Ansatz einer Theorie des Allgemeinen Rechnen'* ('application of a general theory of calculating'). Already in 1940, after his having been drafted into the Wehrmacht (army), he occupied himself with programming problems. Among other projects, he developed a program to play chess. He used the German term *'Rechnen'*, meaning 'to compute' in the widest sense, as he wrote *'Rechnen heißt—aus gegebenen Angaben nach einer Vorschrift Neue Angaben bilden'* [13] ('to compute means to deduce new data out of given data by means of a rule'). He used the term *'Angaben'* to denote data and the term *'Vorschrift'* to denote 'rule' or 'algorithm', as he did not then have at his disposal a term to represent software or program as in today's language. And so, he utilized the then commonly accepted term in Germany for engineering calculations, *'Rechnenplan'*, meaning 'a pattern to carry out calculations'. He thus utilized the programming language he had developed, which contained numeric as well as non-numeric data to describe a full chess program.

By 1943, Zuse had established his own firm, *Zuse Apparatebau*, that employed some fifteen employees. According to a contract with the German Ministry of Aviation he constructed the Z4, an electro-magnetic multi-purpose calculating device with mechanical storage. The Z4 is the only one of Zuse's devices that survived the war. He constructed, also for the Ministry of Aviation, two additional special-purpose devices: S1 and S2.

After the war he was interrogated by the Allies for his work during the War and was brought to the UK in 1946.

Helmut Schreyer (1912-1984)

Schreyer was born in Selben, in the vicinity of Leipzig in 1912 and passed away in Rio de Janeiro in 1984. Unlike Zuse, Schreyer did not write about himself and did not have any pretensions about being recognized as a computer pioneer. The biographical resources regarding Schreyer are very limited. This is perhaps because he was an active member of the Nazi party. In the last years of his life he wrote several papers on his work during the years 1936-1945. But in histories of the computer he appears only in conjunction with Zuse in the writings of others, since Zuse dedicated to Schreyer a respectable place in his biography and in his other publications.

Schreyer spent his childhood in Mosbach, Baden. Between 1934 and 1938 he studied electrical engineering—*Fernmeldetechnik*, today known as telecommunications—at the Technical Higher Education School of Charlottenburg, Berlin. It was there that he met Zuse. It was before electronics appeared as an independent discipline. Even the term 'electronics' was coined only in the 1930s; earlier, it referred to a branch of chemistry dealing with the behavior of electrons. Electrical engineering comprised weak and strong current disciplines (for more on this, see the section that deals with the USA). Schreyer exhibited great talent during his studies as an amateur actor with a great deal of charm. Zuse also acted in an amateur theater, we remember, and it was there that they became friends.

From the outset, Schreyer helped Zuse as a fellow student in the construction of the Z1 at Zuse's parents' home. Their main occupation was to cut thin layers of metal plates into shapes suitable for the mechanical relays, the system of levers and the switches.

As a student, Schreyer worked as a film projector operator in a cinema. He and Zuse were very enthusiastic about the movie *King Kong*, then playing in Germany. It was Schreyer who proposed to Zuse to utilize the film feeding apparatus of the film projector as a tool for the input of the instructions. Zuse adopted this idea and punched coded instructions into exposed 35mm film. Zuse used exposed films because they were much cheaper than new paper tapes. In the film projector every individual picture, every frame of the moving film, is projected against the projection shutter for 1/24th of a second, thus creating the illusion to the human eye of continuity and movement. The developed film serves as a form of information storage media that is retrieved by sequential projection after its editing. That is to say, the order of the appearance of the individual pictures is consistent, one following another. This film projector feeding apparatus was incorporated into all of the devices that Zuse constructed. There is evidence of attempts at Kodak to construct a calculating device by applying photographic film as a storage medium of numerical data.

Schreyer, who was aware to the difficulties of the reliable self-production of mechanical relays, proposed a change to Zuse, first to electro-magnetic and later to electronic relays based on radio tubes. Schreyer emphasized the flexibility and openness of Zuse in adopting new ideas, as shown by the example of integrating the electro-magnetic calculating unit in all his devices. In the Z3 (1941), Zuse also utilized electro-magnetic storage. Zuse preferred to use mechanical storage in his Z4 model (1943), since it used only one quarter of the space compared to the electro-magnetic equivalent.

Schreyer claims that Zuse developed a special abstract logic for binary switches for mechanical, hydraulic, electrical and electronic switches. The Zuse archive corroborate this.

Schreyer did not satisfy himself with just an electro-magnetic calculating unit; he argued that since electrons move faster than mechanical parts, it was feasible to use switches (*schaltungs*) and relays based on neon tubes (*glimmlampen*) to this end. Later on, he proposed to use electronic tubes (*electronerohre*) too.

By 1937, Schreyer succeeded in devising a logic relay and switches system based on neon tubes, or as he called them, *'Rohrenrelais'* (tube relays). This was a type of a flip-flop enabling the creation of three stable states analogous to the logic of 'and', 'not' and 'or'. They had not yet been seen this way: such terminology is anachronistic, since the first patent for logic gates was only issued in the USA in 1941. Still, these (logic) gates served to create components for calculating or storing numerical data. Schreyer had no former knowledge of Wynn-Williams' work of 1931 about the binary counter on vacuum or low pressure gas tubes [14]. Nor were others in the field then aware of him. He was even unaware of the famous work of Eccles and Jordan (1919) on the electronic trigger (flip-flop); he learned about the electronic flip-flop only after the War [15]. Schreyer proceeded concurrently and independently of what occurred in the USA and the UK in the development of his electronic calculating unit. At that time many were occupied with the construction of electronic counters. In spite of the transformation from a counter to a calculating unit being possible and simple, the development of an electronic calculating unit is much more advanced. Schreyer enhanced his work at the most preliminary point, with the calculation operation corresponding to the three elementary operations of the prepositional calculus of which he was unaware, and developed electronic components suitable for those three functions, based on an imitation of electro-magnetic relays by means of vacuum tubes. The neon tubes served also as a storage element. These ideas had led by 1938 to a proposal to develop a calculating device comprising some two thousand vacuum tubes and several thousand neon tubes. He made this idea as a part of his studies at Charlottenburg, but it was rejected. Instead, he succeeded in constructing a calculating unit that contained some one hundred tubes to represent a decimal number up to the tenth figure in the binary notation. He applied for a patent on the neon and radio tube relays on November 19, 1940, entitled *'Schaltung von Glimmlampe und Elektronenrohre als Rohrenrelais'* (German patent application 1704).

The idea of the large electronic calculating device (of two thousand tubes) was then far ahead of parallel designs in the USA and the UK. Were it constructed, it would be equal to the quality of the electronic automatic program-controlled digital calculating machines in the USA and the UK of the end of the 1940s.

Helmut Schreyer's PhD dissertation was titled *'Das Röhrenrelais und seine Schaltungstechnik'* (Tube Relays and their Switching Techniques), dating from August 30, 1941 and comprising 44 pages. Schreyer gives an account of the principles of switching and the logic of relays to create electronic storage and calculating circuits. The neon tube requires a starter to ignite the ionization process of the gas; this 'stimulus' provides the electrical circuit with two well distinct discrete states equivalent and analogous to connect-disconnect states of the switch.

By 1942 Schreyer had succeeded in acquiring from the Telefunken company special radio tubes by means of which he constructed a pilot-experimental model of a smaller calculating unit comprising only two hundred tubes. The financing of this effort came from the Institute for Aerodynamic Research, the very same organization that also financed Zuse's Z3. However, this pilot model of Schreyer's was destroyed during an air raid on Berlin by the end of 1943. In this experimental model Schreyer utilized decimal notation with binary technology and the above mentioned logic of the three state switches. A more advanced model was constructed during 1943 between the bombing raids, and had been completed by 1944 and installed in Göttingen. Later on, he turned to develop a binary parallel calculating unit. He also developed a parallel storage unit of neon tubes for binary counters. On June 11, 1943 he applied for a patent: *'Electrisches Kombinationsspeicher'* (an electrical combinatorial memory). In 1944 he also designed vacuum tube converters that changed decimal base notation into binary base notation.

To repeat, Zuse attributes to Schreyer the development of many ideas of calculating instrument during the period 1935-1945, in particular the passage and adoption of electro-magnets and radio tubes. For further details, see Zuse's biography *Der Computer—Mein Lebenswerk* (*The Computer: my Lifework*). I discussed this with Zuse on September 1986 [16].

In Germany, in 1941-1942, the scientific and technological establishment rejected on the spot the proposal to develop a device like Mark I. In 1944 the same people pressured the experts in calculating devices to develop tools identical to Mark I. They soon displayed some results at IPM, Darmstadt. Interestingly, it was the same German scientific establishment in both cases. It was their learning of the very existence of Mark I that entirely reversed their position. Once they learned that the Americans were leading the development of automatic program-controlled digital calculating machines, they deemed German prestige injured, and they provided considerable resources to change the situation [9].

At the beginning of 1945, Schreyer was evacuated from Berlin, and so ended the development of electronic calculating instrument in Nazi Germany. Schreyer migrated after the war to Brazil, where he worked in communications. Unlike Zuse, Schreyer had joined the Nazi party by 1933. Schreyer used his influence in the Nazi party to release Zuse from military service in a letter dated October 15th, 1939, and emphasized in that request the multi-purpose qualities demonstrated in Zuse's machine, including its possible utilization for the war effort:

> 'Here, then we have a universal computing machine.. In the course of several years, Konrad Zuse, with my help, built a computing machine containing mechanical relays which were developed also by him... The work however has been interrupted because of the call of Konrad Zuse for military service. Since it is a case of building a model it is necessary, for the development of the final machine and for the production of the model, for Zuse to be allowed to carry out the work. If one is interested in the military applications of the machine, then contact between the appropriate military service department and Zuse should be made... With a computing machine with valve circuits, that is one with grater calculation speed ... will be able to do 10,000 operations per second.

> 'We are here concerned then with a computing machine which can be of valuable assistance both for military equipment as well as in its applications. For the construction of the computing machine only simple relays are required because it carries out its calculating operations in a binary system, which means a considerable simplification in the construction of computing machines.'

Zuse and Schreyer were totally unaware of the work of Babbage, Turing or other developers—in Germany or abroad. There is nothing more to consider in this context.

The United States

Here, the story will focus upon four developers and two co-developers in the USA who as a group designed, developed and constructed automatic program-controlled digital calculating machines.

George Robert Stibitz

Stibitz was born in 1904 in York PA. His primary education was in Dayton OH, where his father served as a professor in a theological seminary. There he studied in a special experimental school established by Charles Kettering, the inventor of the modem automotive electrical starting system. At that school Stibitz carried out experiments in chemistry, physics and electricity and constructed various electrical instruments. At the beginning of the 1920s, when radio broadcasting started to become common (commercial broadcasting was introduced in 1926), he constructed by himself a crystal radio (like Atanasoff) at his parents' home. Even by then, he had begun to use vacuum tubes and was quite familiar with contemporary electricity and electronics. In 1926, he received his Bachelor's degree in Philosophy from Denison University, Granville OH, and his Master's degree in Science in 1927 from the Union College in Schenectady, New York State. The title of his Master's thesis is, 'Acoustic Wave Propagation in Curved Pipes'. In 1930 he completed his PhD studies in Mathematical Physics at Cornell University, Ithaca, New York. His dissertation was titled 'Vibrations in Non-Planar Surfaces', although, according to the official 1973 biographical publication of Dartmouth College, where Stibitz's personal paper collection is kept, the name given to the dissertation is 'Non-Planar Membranes'.

Electricity then was studied as a part of physics. During his Bachelor studies Stibitz constructed in the laboratory various electrical instruments. His inclination was towards mathematics, but he took many courses in physics related to electricity and electro-magnetism. While studying mathematics, he rarely used calculating machines, because they were then rare and expensive. The most common tool to carry out calculations was then mathematical tables and slide-rules. His slide-rule remained displayed in a place of honor above his desk on the wall in his office at Dartmouth College. I visited him there on October 17, 1986. Though he was by then Professor Emeritus, he remained active in the College until his death in 1995. While working on his doctorate at Cornell, he continued to pursue his interest in electricity. His PhD tutor was expert in thermionic valves.

As Stibitz received his doctor degree, his tutor advised him to proceed with his research at Bell Laboratories rather than at General Electric, where he had worked for one year in 1926-1927, between his receiving his master's and his doctoral degrees. While working at General Electric he gained a great deal of experience with thermionic tubes and electro-magnets. His main scope of work there was the research of disturbances to radio communications. Stibitz and one other person there were doing the research in a particularly large house located somewhere outside the town. As it was very cold there, they tried to be there as little as possible. To this effect, he constructed a remote control operating apparatus, activated by means of a telephone dialing system through a telephone found inside the house. The radio transmitters and the testing equipment were activated according to certain digits dialed in order to trace malfunctions and disturbances during transmission. This way Stibitz gained considerable experience in electricity and electronics. I confirmed this in a conversation with Stibitz during our meeting on September 17, 1986. Incidentally, this very laboratory of General Electric also accommodated Charles Steinmetz, who developed the theory of applying complex numbers to the analysis of the behavior of electrical networks. This theory was subsequently applied to telephonic (wire-line) communications.

During his early days at Bell (1930), where he worked as a mathematician, Stibitz also studied problems related to counting circuits made of telephone electro-magnet components. At Bell people did not belong to predetermined working teams: 'whenever a problem arose, we used to turn one to the other and discuss the issue'. In 1936 he joined another research group at Bell. He had already worked for three years on electrical circuits and 'was happy in his share', because in the 1930s, during the Great Depression, it was very hard to find a job, particularly for a mathematician. He was then married; his pressing finances compelled him to build his house with his own hands. He then devised a heating system and other improvements. He invented then a propeller capable of changing length and form to achieve maximal effectiveness and efficiency for aircraft propulsion. He built by himself an amplifying system for a turntable, anticipating modern High-Fidelity systems by incorporating electronic and electro-magnetic tool, such as the pick-up of the turntable arm. He also devised an electro-mechanical counter, producing some two hundred pulses in a second, on a multi-ball pendulum for which he received a patent by 1935. He also constructed an electrical transformer. As he was short of money, he typically used junk equipment and parts which he acquired from Bell. The main attraction at his home was an electric gravitational train operating in his yard that people could ride on, to the great delight of children and visitors [17].

In about 1936, he was appointed to work on the improvement of the quality of the standard U-shaped telephone electro-magnetic relay used at Bell. He decided to examine the properties of the electro-magnet from its very elementary foundations and searched for a mathematical model that could best describe such a relay. Between November and December 1937, as a hobby during his leisure time, he came to develop the binary adder. Only then did he grasp that it was but an extension of an idea he had already learned during his school days at the experimental school at Dayton. According to his account, the study of the binary notation base and the transformation from one base to another was then considered something extraordinary and particularly complex. Stibitz points out that he became conscious of binary logic thanks to *Principia Mathematica* of Russell and Whitehead. He claims that then he had heard nothing and remained unaware of the works of Babbage, Turing (1936) and other mathematical logicians. He likewise claimed that he had no idea about the programs presented in 'Instrumental Analysis', the 1936 paper of Vannevar Bush and in 1937 memorandum of Howard Aiken. He worked independently at Bell within the framework of a team of applied mathematicians who used to work together or independently with telephone engineers in an informal atmosphere. Such a five-member team used to have a supervisor. The mathematician F. C. Fry, who was then the director of the mathematical section of Bell Laboratories, had developed personally by 1936 an isograph, an analog device to deduce square roots. The group worked on electrical circuits based on valves and amplifiers. The latter are thermionic tubes capable of amplifying the output current or voltage from a given weak input. This was the result of Lee De Forest's invention of the Audion in 1906. They were interested in the mathematics of amplifiers and looked for a mathematical description of the amplifier in order to reduce background noise on telephone lines. Stibitz said to me, 'what Peterson [the electrical engineer] did intuitively, I checked mathematically'. His department included a group of women employed in calculations. He told me that these ladies were called 'calculators'. Personally, we remember, he preferred to use the slide-rule. During his studies in Denison College he took a course in astronomy and learned how to use mathematical tables and calculating machines [18].

Stibitz greatly illuminates the differentiation and the separation between the concepts of practical mathematicians and telephone engineers. During our discussion on October 17, 1986, he told me,

> 'I did not know the connections between the relays. The terminology used for circuits was a connection in a series or the connection in parallel [for resistance or conductors according to the laws of electricity]. The people that designed circuits thought in terms of what a relay does to a circuit. They imagined in graphical drawings and have seen a picture. I knew two or three such people; they started with a general picture from a drawing. This was not science, this was art. What could be written on a piece of paper was as reality. If one wanted a design, one made a drawing of an abstract circuit and used the common algebra with its zero or one limitations [one for a flow of current, zero for neutral], not Boolean algebra.'

Stibitz also pointed out this.

> 'The telephone people were divided into two groups, those of switching and those of transmission, and these people did not talk between themselves. They did not read binary, but everything was yes or no'.

Stibitz became acquainted with Turing during Turing's visit to Bell Laboratories at the beginning of 1943. Turing then was involved there with C. E. Shannon on a highly classified project. Referring to the Ballistic Computer, Stibitz stated during our conversation,

> 'I wanted to tell him about my computer, but Turing showed no interest in it, maybe he had already seen my computer.'

William Frederick Friedman (1891-1969), chief US Army cryptographer, showed an interest in the device that Stibitz had developed. There is some indication from Stibitz that it was applied for cryptography; this exceeds the scope of the present work.

As for Stibitz's awareness of Babbage, he told me the following during our above referenced conversation.

> 'I have met or spoken with Aiken. I was introduced to Aiken by Dr. Fry, who visited at Harvard and heard about the computer that he built there,

> after the Relay Computer was operational. Fry said that Aiken had told him that he had constructed a similar device to Babbage's.'

By then, Stibitz had not yet read anything by or about Babbage [19].

> 'I constructed the 'K' Model [Kitchen Model] in November 1937, everything happened in a period of about thirty days in November of 1937, because in December the full adder was already ready'.

Stibitz says, he drew the adder's circuits and later built it. To my question, how did it occur to you at all to construct such an adder? he replied,

> 'I took some relays home for a week and made various connections between them to see what may be obtained from these integrations. As for the notion of binary, I was made aware of it through lectures given some ten years earlier by Vilaro [?]. When I brought the adder to work, people were impressed with the idea, but indicated its impracticality. We all agreed as to the feasibility of constructing a calculating machine with it. There had already been an earlier demand for a mechanical hand calculating machine and its adaptation to perform calculations with complex numbers. Nelson Sowers, who worked in another Bell laboratory, proposed verbally to construct such a machine, a thing that had been spread among the members of the laboratory. I thought that such calculations could be performed mechanically. However, when Dr. Fry saw my relay adder, I was already working on the design of a full adder. Dr. Fry then showed me the idea which was going around about the mechanical calculating device for solving complex number problems. I told him that it would be much easier to construct such a device from relays'.

The name given to the device at the beginning was 'calculator' and not 'computer', as it appears in the title of the article of August 1942.

> 'At the outset there was only the adder, I did not refer to anything else. The discontinuity from the wheel was explicitly evident.' And Stibitz concludes, 'my device did not result from any need, but, from sheer curiosity.' [20].

My survey of Stibitz's biography for the sake of our inquiry into the history of computers and his contribution to the development of the automatic program-controlled digital calculating machines will end here. But I will refer in other places to his 1941-1945 involvement as a technical adviser to the National Defense Research Committee (NDRC) Division 2, where he was in charge of the development of fire-control technology, such as his reaction to Atanasoff's device at Iowa College or his relation to the ENIAC project, which was taking place at the University of Pennsylvania.

Remaining within the limits of our discussion that took place at his office at Dartmouth College, Hanover NH, on October 17, 1986, Stibitz raised the issue of writing his own biography. His writings and documents that were in his possession are now kept in the Barker Library at Dartmouth College and are organized in an exemplary manner. He said that he had not been aware of C. Shannon's famous Master's thesis that describes the optimal relationship between Boolean logic or algebra and the design of the most economical switching circuits. One of my concluding passages here, indicating the transformation 'from the art of designing switching circuits to the creation of a scientific discipline', paraphrases Stibitz's statement regarding the design of switching circuits. In an internal memorandum of April 22, 1938 (Box 20878) with the heading 'Relay Circuits and Boolean Algebra', he explicitly mentions Shannon's work. In another memorandum of May 6, 1938, 'An Application on N Dimensional Boolean Algebra to Relay Circuits', and in three additional internal memorandums—'Solution of Boolean Circuit Equations' of May 20, 1938, 'Some Results on Minimal Relay Circuits' of May 32, 1938, and 'Reducible Relay Networks' of June 1, 1938—there are references to those issues as treated by Shannon.

During the period 1939-1940, Stibitz wrote several memoranda (ten or so) dealing with the 'Symbolic Treatment of Certain Network Problems', on the difference between binary and decimal numerical systems and circuits to execute calculating operations in binary notation. These documents show that the idea of constructing a calculating machine for complex numbers had been raised to Dr. Fry by F. J. Scudder.

A memorandum of August 19, 1938, 'Detailed Operation of the Complex Computer', has a detailed account of Stibitz on the complex computer and its operating method; it uses the term 'computer' (see above).

An important point concerning Stibitz's biography while at Bell relates to the particularly close cooperation formed between him and S. E. Williams, a telephone and switching engineer, who, together with E. G. Andrews, proceeded with the development and construction of electro-magnetic calculating devices at Bell.

Stibitz was a very modest person, who avoided speaking about himself, and who tried to avoid taking any stand as to the history of computing in general and the history of the computer in the USA in particular. In our discussion he said from the outset that Atanasoff was the father of the idea of the electronic computer. I drew his attention to how Atanasoff turned to, among others, the NDRC to get assistance for the construction of his device, how the matter had been diverted to Norbert Wiener for assessment, and how Stibitz was listed as one of the addressees to this letter. Wiener's answer to the NDRC referring to Atanasoff's technique is found in a letter dated October 29, 1941. On January 24, 1942 an additional reference to Atanasoff's documents, stating that they were returned personally by Wiener to the NDRC. In response, Stibitz claimed that, while not recalling these events personally, he was nevertheless inclined to change his mind as to Atanasoff's paternity claim over the electronic computer.

Remark:

In 1940 Norbert Wiener was chief adviser to a sub-committee of electrical and mechanical calculating aides for the NDRC. Until 1945 he was a member of an interdisciplinary group at MIT that researched the mathematical aspects of the guidance and control of anti-aircraft fire.

John W. Mauchly (1907-1980)

Mauchly was born on the 30th August 1907 and passed away on 8th January 1980. Until 1913 his parents lived in Hartwell OH and in Cincinnati OH. It was there that his father completed his PhD studies in Physics at the University of Cincinnati. By 1913 the family had moved to Washington D. C., where his father became associated with the Department of Terrestrial Magnetism at the Carnegie Institution of Washington. After a short stay in the Columbia District, the family moved once more, this time to Chevy Chase MD. From the third to the eighth grade Mauchly attended E. V. Brown Elementary School in Chevy Chase, D. C. During the years from 1921-1925 inclusive, he attended McKinley Technical School in downtown Washington. Mauchly also took part in vocational courses there, including exercises in workshops and laboratories. His good grades qualified him for the Maryland State scholarship to the Johns Hopkins School of Engineering at Homewood, Baltimore MD. He received two scholarships in parallel, one to the School of Engineering and the other for philosophy, so he was asked to give up one of them [21]. By means of the awarded scholarship he studied Electrical Engineering at Johns Hopkins University for two years, 1925-1927. Then, in the fall of 1927, he asked to be transferred to the Graduate School of Physics at Johns Hopkins. This was under a special program that permitted qualified students to proceed directly to an advanced degree without receiving a Bachelor's degree. He was already demonstrating an interest in finding an effective multi-purpose method for solving problems. He continued his studies toward a Doctorate of Philosophy in Physics, which he obtained from Johns Hopkins on February 12, 1932 [22]. In a letter to his sister Martha of 21st March 1925 he wrote,

> 'It is my folly which prompted me more than once to formulate one rule for every situation, and to attempt to solve every problem by the same rule.' [Van Pelt, Box 1, File 2] [23].

His courses at Johns Hopkins had been mostly in mathematics and physics, and his advanced work was both experimental and theoretical. His PhD dissertation was on molecular spectroscopy, titled 'The Third Positive Group of the Carbon Monoxide Bands', and its results were published in the *Physical Review* in January 1933 as a joint paper with Dr. Gerhard Heinrich Dieke (1901-1965), his PhD adviser. During the academic year 1932-1933 he remained at Johns Hopkins as a research assistant to Dr. Dieke. While working on his dissertation and during that additional year at Johns Hopkins, he had the opportunity to perform many numerical calculations using desk calculators. Just as one example, according to his own *Résumé*, Mauchly derived new methods for calculating energy levels of molecules in quantum chemistry that were more efficient than those suggested to him by the university professors. According to another version, he was a research assistant to Professor Joseph Eachus and was required to carry out considerable calculations of energy levels of Formaldehyde.

The wide ranging correspondence from his studying period at the university, reveal that he turned to many places to find a job during his summer vacations and upon his final graduation, but was turned down everywhere. One rejection letter, for example, was the reply of May 12, 1926 from the Chase Peake and Potomac Telephone Company [24].

In 1933 Mauchly was appointed as head of the Department of Physics at Ursinus College, in the vicinity of Philadelphia PA. It had one member: Mauchly himself. He accepted this offer as he had no other options, as the Great Depression was not yet over. He held this position until 1941. During those eight years he extended the scope of the courses offered to the undergraduate students at Ursinus. In particular, the advanced students were exposed in the laboratory to experiments involving the use of vacuum tubes and electronic equipment. His paper collection at Van Pelt Library's special collection at the University of Pennsylvania, contains a great deal of correspondence on his acquisitions of electric equipment and other components for the physics laboratory. At that time, he also enrolled at the evening Graduate School at the University of Pennsylvania, where Professor Knox MacIlwain instructed him on the theory of vacuum tubes. He also acquired electronic equipment for the physics department of

Ursinus College, such as a cathode oscilloscope and a variety of components needed for experimental work with electronic circuits. There was no such equipment at Ursinus College prior to his arrival, nor any prior attempt to expose the students to electronic devices. Mauchly also bought such equipment for himself, the best he could afford, for electronic computations. One of his first personal purchases after his arrival at Ursinus was a second-hand Marchant desk calculator, of the same type he had used at Johns Hopkins. The purpose was to continue his work on the calculation of energy levels of molecules, which he did until discovering that others were solving these problems faster, using IBM punch card equipment. Then he turned his attention to the statistical analysis of large masses of weather data. Assisted by a team of students (paid by the college with grants from the National Youth Administration), he processed a great amount of raw weather observations, so that they could be treated statistically to test various hypotheses with the intent to improve weather forecasting. To make the data processing faster, he immediately designed and built synoptic map and a useful device for computing atmospheric tides, known as a Harmonic Analyzer. It was an analog device that had sufficient accuracy for its purpose; it was much cheaper than anything that could have been built to do the same work digitally. Some of his students for data processing used it.

At the same time, he constructed a digital device designed to encipher and decipher alphabetic text in what was new back then. It employed gas diodes (small neon indicator lamps; on this, see also the section on Schreyer) in a circuit that corresponds to a function table. Mauchly states that 'so far as I know, this use of non-linear diodes had not been anticipated by others' (see my comment in the previous sentence). Soon after its construction, the device was shown to the Army Security Agency. The top ranking US cryptographer W. Friedman was among those who examined the device. Mauchly made no further development of this device, although I have found evidence that such a device was developed at the beginning of World War II by the firm NCR. It is worth mention that in a 1957 book William Friedman and his wife Elizebeth Smith Friedman (1892-1980) refuted the view that Francis Bacon is the real author of Shakespeare's writings [25].

Mauchly's paper collection has a considerable correspondence from November 1934 onwards regarding radio tubes, inquiries as to their properties and utilization.

Mauchly showed also an interest in educational surveys, programs and curriculums at high schools, colleges and universities. He worked together with the educational psychologist Benjamin D. Wood (1894-1986) of the Cooperative Test Service of the American Council on Education [26].

I think that Mauchly was aware of Boole's work. His paper collection has a manuscript of nine pages, apparently of the years 1935-1937, or the period of his studies at Johns Hopkins, that discusses Boole's work [27]. There is also an orderly account on the calculations of compensations in electrical circuits to avoid errors. His study copybooks of the years 1931-1932 show that he was well aware of how to make calculations with electrical resistors and their application to the difference calculating method. A physics textbook of 1927, *Electricity and Magnetism*, describes many experiments in electricity and magnetism. He also studied quantum mechanics in German and French [28].

During 1934-1936, he tried to deepen the use of slide-rules for scientific calculations, and to this effect he composed a manual pamphlet with operating instructions after finding that

> 'Many students never learn to use the slide rule, but waste many hours with fruitless calculations because of a belief that the complexity of a slide rule can be mastered only by a superman.' [29].

From 1925 on, he made great use of the typewriter. His type-written reports on electrical engineering studies reveal the importance, as accorded back then, of two events in the history of electricity and the knowledge derived from it: first, Ørsted's experiment of 1819 and second, the publications of Faraday and Henry Joseph from 1831 on electro-magnetism. Mauchly's copybook on electricity has a report on a lecture of December 18, 1925:

> 'In the next century [the 19th] there followed a practical application of the new knowledge of electricity, and in 1820 Oersted a Dane discovered the magnetic effect of an electric current. Then Ampère and Weber conducted experiments in electro-magnetism and in 1831 Michael Faraday, an Englishman, Joseph Henry an American demonstrated the principle of electro-magnetic induction. These two discoveries form the keystone of all applications of electricity. Of such applications, the first to be made was the telegraph, in 1840.' [30].

This provides some notion as to the way of thinking that prevailed then, at least at Johns Hopkins. A hand-written report of a lecture given by Professor William B. Kouwenhoven (1886-1975) on 'The Field of Electrical Engineering' of January 8, 1926 presents the structure of the electrical engineering discipline:

> 'Heavy Current field and Light Current field. In the Heavy Current work such as powerhouse construction, operation efficiency of power conservation is the main goal of electrical motors and electrical furnaces. In the Light Current we may place electrical communication, accurate results are the primary consideration. Telegraph, telephone radio. Each of these fields is linked to the vacuum tube, which has opened up to us a new era in the history of electricity. The thermionic valve may also play a part in the Heavy Current field, in transmission of high potential direct current.' [31].

All of these lectures emphasize the importance of measurements and tests. These lecture reports, found in Mauchly's collection of papers, deal more with history than with practical knowledge.

One of the most fascinating items found in Mauchly's biography is a written piece of homework, presented on October 12, 1925, bearing the heading 'My Choice of Vocation'. The date of it is printed on the rear side of the last page, so it may have been placed there on another occasion. Nevertheless, it seems to be from 1925-1926. It contains the following:

> 'Things electrical have interested me since my 12th birthday. I must have had some sort of knowledge of electric circuits before I could have succeeded in even this small attempt [at constructing an electro-magnetic bell].'

Mauchly recounts how he learned so much from his father, who was in charge of physics studies in a high school. He recalls:

> '…taking apart and repairing an old adding machine. How it is done and why it is done that way have always been my question mentally if not expressed in words. But however the field of mechanics appealed to me, that of electricity will always hold the place of honor, and disregarding all other considerations, I believe that this should be reason enough for pursuing my course in electrical engineering.' [32].

Nevertheless, two years later he left electrical engineering and moved to physics.

In 1939, Mauchly applied to Moore School for Electrical Engineering for a planned training course on 'The Theory and Design of Calculating Means'. The course was canceled due to a lack of candidates.

Mauchly showed great interest in the development of calculating means in the USA. We find him in September 1940 at the Hanover NH meeting of the American Mathematical Society, watching and inquiring at the demonstration of Stibitz's Complex Computer, although, to my surprise, his name does not appear on the list of participants. Mauchly met there Norbert Wiener and they had a discussion on calculating devices. Mauchly's second wife, Kathleen, in an article of April 1984, writes that Mauchly and Wiener agreed that 'electronics is the way to go' [33]. I did not find a trace of such a meeting either in Mauchly's or in Wiener's papers.

A letter dated October 5, 1940 from Mauchly to the mathematician Derrick Henry Lehmer says, 'As a physics teacher, I am only a poor amateur in the theory of numbers and such things, but I have always had an active interest in calculating machines and methods.' Mauchly expressed his keen interest in Lehmer's calculating machine. He then added: 'Our own effects in machine calculating go in the direction of, for instance, an electrical harmonic analyzer for use in statistical work on weather cycles.' His letter ends with an account of a test Monroe calculating machine a few days earlier 'for breaking a large number into factors or providing its prime.' [34].

This was precisely the domain that Lehmer was involved with, methods and mechanical, electro-magnetic and photo-electric devices for the deduction of prime numbers by the sieve method.

There is also a letter of interest sent to Mauchly referring as to his work as a 'computer':

> Carnegie Institute of Washington, D. C.
>
> Department of Terrestrial Magnetism
>
> June 27, 1938
>
> Dear Dr. Mauchly,
>
> This will confirm the verbal arrangement made this morning for your employment for two months from July 1938 as Temporary Assistant Physicist and Computer at $100 a month. [35]

On 28th December 1940, at an annual meeting of the AAAS (American Association for the Advancement of Science) Mauchly presented his calculation results on weather prediction, deduced by means of the electrical harmonic analyzer that he had constructed for this purpose. The accuracy of these results was within 1%. At this meeting a relationship between Mauchly and Atanasoff began, which was to be momentous later on, as will be discussed in some detail further on.

In summer 1941, the Moore School of Electrical Engineering of the University of Pennsylvania offered to train physicists and electricians as part of defense training course sponsored by the government. Mauchly was accepted into this course. It started on June 23, 1941 and he spent several months full-time there. There he met for the first time his life partner and collaborator J. P. Eckert. At the end of that course Dr. Carl Chambers, who was in charge of the course and also a professor at Moore, asked him to join the staff of the Moore School. Mauchly resigned from Ursinus College and remained at the Moore School until March 31, 1946, when he and Eckert were compelled to resign after refusing to sign away their rights for any future invention made within the framework of the Moore School.

As a member of the Moore School, Mauchly worked on various projects associated with the war effort. One of these was for the Signal Corps, the object of which was to calculate antenna radiation patterns for radar use. He organized a team of human computers, some of whom were students, some not, who under his direction used mechanical calculators to compute required results. One of the difficulties was in securing calculating equipment. To buy a new one needed prioritization. So he borrowed from existing supplies at the Wharton School of the University of Pennsylvania and also used equipment that he was able to bring with him from Ursinus.

During this time, he was still using mechanical calculators, and he repeatedly urged the Moore School's staff to give consideration to the development of automatic electronic devices. He claims that his confidence that the development of such equipment was possible rested on two considerations. One was the considerable amount of experience he gained at Ursinus and his knowledge of the then existing technology used in measuring cosmic rays that would lend itself directly to new computational problems. The other was the agreement with him on the part of Eckert, who, after reviewing the plans outlined by Mauchly for electronic calculations carefully, did not see any reason why such circuits could not be designed to achieve the high reliability necessary [36].

Dr. Chambers suggested that a desirable step towards possible action on Mauchly's ideas would be to make a written proposal and pass it around the various faculty members. This Mauchly did. He circulated a memorandum in August 1942, titled: 'The Use of High Speed Vacuum Tube Devices for Calculating'. It may be considered one of the most important documents in the history of the invention of computing [37]. The original version of this memorandum, however, was misfiled and only recovered from the Moore

School's archives some thirty years later, with a hand-written note attached to it, bearing the date of 1-12-1943 (January 12), most probably by Brainerd:

> 'Read with interest. It is easily conceivable that labor shortage may justify development work on this in the not too far distant future.' [38]

Mauchly saw to it that his idea would disseminate by other vectors as well. In 1943 the Ballistic Research Laboratory (BRL) of Army Ordnance at Aberdeen Proving Ground (APG) was working closely with the university to expedite the preparation of artillery firing tables. The Moore School used a difference analyzer to this effect; Joseph P. Chapline, Jr. maintained it. He was a former student of Mauchly at Ursinus, familiar with Mauchly's earlier work and interested in electronic computation. Through Chapline, the various persons visiting the Moore School came to know of Mauchly's proposals, in particular, Dr. H. H. Goldstine, then an Army Lieutenant at the BRL. Goldstine asked for more information regarding the proposal sometime in March 1943 (according to the version provided by Mauchly; Goldstine and Chambers both provide different versions of this issue). Only by then, was it found that the original document of August 1942 had vanished. It has since been reconstructed by transcribing the original stenographic notes kept by Mauchly's secretary. At Goldstine's request, a more detailed and official proposal was prepared. It was submitted to the BRL as soon as April 8, 1943. This is Mauchly's account; it is inaccurate. The first draft of that proposal report had been dispatched personally by Goldstine to the BRL on April 2, 1943, while the final and more comprehensive report, bearing the date of April 8, 1943, was delivered on April 9. Most scholars are unaware as to the existence of these two reports (Electronic Diff. * Analyzer, and Electronic Difference Analyzer). A third document is a corrected version of the first draft (and thus, also, corrects many erroneous conclusions derived from it) [39]. During April-May 1943 several meetings were held between army, government and university authorities as to the feasibility of such an undertaking. By June 4, a contract had been signed between the Army and the University, on an experimental project basis, to test the feasibility of the Moore School's proposal. It took effect from June 1, 1943, although the work on it had already begun at the end of May. Mauchly was appointed as Chief Adviser to the project. The project was termed by the University as 'Project X' and the device was termed by the Army (Colonel Paul N. Gillon) as 'ENIAC'—Electronic Numerical Integrator and Computer.

Mauchly had no previous knowledge of the works of Babbage or Turing. Yet, to repeat, he took great interest in the other developments of calculating means in the USA. He had seen Stibitz's Complex Computer and had the chance to inspect Atanasoff's device. The meeting between Atanasoff and Mauchly had grave implications in the 1960s and 1970s; this will be dealt in depth and extensively later on. There is also no evidence that Mauchly had read 'Instrumental Analysis' of Vannevar Bush of 1936, or that he had any notion of Aiken's work prior to his own memorandum of 1942.

Howard Hathaway Aiken (1900-1973)

Aikenwas born in 1900 in Hoboken NJ; he died in 1973 in Saint Louis MO.

The biographical sources about him are very poor. What is found regarding Aiken in the Harvard archive belongs to the period 1944-1961 [40]. According to Professor I. B. Cohen of Harvard University, the sources prior to his military service have since gone to ruin because of improper storage at one of the Navy bases. Only his famous 1937 memorandum 'Proposed Automatic Calculating Machine' survives [41].

A dispute between Aiken's family and Harvard University on the heritage rights of his inventions prevented the transfer of extant documents at the family's disposal.

Interviews related to his biography are probably rare because he was a very busy person; there is no trace of any interview with him prior to 1937 [42].

Professor I. B. Cohen University and H. S. Tropp, then of the Smithsonian Institution, interviewed Aiken over several consecutive days. In the interviews they refrained from going into details, postponing it for further meetings, as they thought that he was in excellent physical condition that permitted them, after analyzing the primary interviews, to go into more detail into whatever issues that might arise. Unfortunately, Aiken died three weeks later from heart failure [43]. These recorded interviews are under protection and any use of the stenographic text of the interviews of some 220 pages requires the approval of his widow.

Aiken was raised in Indianapolis, Indiana. There he attended Arsenal Technical High School, considered an excellent school. Because of financial problems, he was obliged to support the family while attending school by working nights as a telephone operator at a local gas and light company. He worked twelve hours a night, thirty nights a month. The school supervisor arranged a special series of examinations for Aiken that enabled him to accelerate the learning period. The supervisor encouraged him to carry on with his studies at the University of Wisconsin, after finding a similar job for him, as a telephone exchange operator, at a gas company in Madison. After graduating from high school, Aiken moved to Madison, Wisconsin, to study at the University there. Power engineering then generally belonged to electrical engineering and, more specifically, heavy current engineering, such as powerhouse construction and operation, efficiency of power conservation, generators, turbines, electrical motors, electrical furnaces and power networks. After graduating with a Bachelor of Science (BS) degree by 1923, he carried on working for another twelve years in the very same gas company in Madison, only this time as its chief engineer. In 1935 Aiken returned to academic studies, first at the University of Chicago and later on at Harvard, where he received a PhD in physics in 1939 [44]. His PhD dissertation was 'On the Theory of Space Charge Condition', guided by E. L. Chafe, who was considered an expert in vacuum tubes and electrical circuits. In the framework of his dissertation he was required to make calculations of numerical solutions of non-linear differential equations, granting him the experience that led him to the development of two electro-magnet-based spatially-oriented calculating devices for solving problems with polynomials. It has not yet been confirmed to my own satisfaction that these devices were electro-magnetic, and there is no further evidence to this effect [45]. The first device was designed to solve problems with simple polynomials. The other device was intended to solve much more complex problems with polynomials. While analyzing the two types of problems he reached the conclusion that, logically, the two machines were identical, differing only in the type of information input and its treatment [45]. Hence, he turned to the construction of a multipurpose device that could treat all types of mathematical problems, as is exhibited in his memorandum from November 1937 [46]. In this memorandum, Aiken mentions, within the scope of the historical introduction, Babbage and other 'computing devices pioneers'. I reckon that Aiken read about, and more precisely copied, very superficially, Babbage and other computing device developers from a catalog prepared by D. Baxandall (1926) for the London Science Museum (as well as for the *Britannica* 14th edition of 1929), as well as from E. M. Horsburgh's (1914) *Napier Tercentenary Celebration* and the popular book of J. A. V. Turck (1921), titled *Origin of Modern Calculating Machines.*

At first, Aiken contemplated basing his proposed calculating device on the Monroe calculating machine that would be integrated with an electric connecting plug-board like that of a manual telephone exchange. One can easily trace the influence on Aiken of his years spent gaining experience as a telephone exchange operator. In an interview given on April 22, 1937 to the chief engineer of Monroe, G. C. Chase, Aiken outlined the concept of his calculating device and explained what could be accomplished with it in the of mathematics, natural science and even sociology. What he had in mind at that time was the construction of components that could be resolved as constructive mediators. The device was aimed to execute automatic calculations by means of the four elementary arithmetic operations according to a prearranged series of controlled operations, storage, and registration of the values entered. These would all operate under a sequence of controls that would react automatically to symbols of the device and produce a printed output of everything going through the device, including the desired final results. Chase saw practical and economic advantages in Aiken's proposal and he tried to persuade the firm's directors to enter in the venture to develop it. After several months of debate, the Monroe firm rejected Aiken's proposal. Chase encouraged Aiken to turn to IBM [47]. The meeting between Aiken and the IBM representatives led (in 1939) to the development of the 'Automatic Sequence Controlled Calculator (ASCC), also known as Harvard Mark I, the construction of which was completed by 1943.

Aiken had no previous knowledge of Turing's work (1936). I am of the opinion, in disagreement with most scholars, that Aiken became aware of Babbage's work on the Analytical Engine only after having conceived the idea of his own device. By happenstance, a little after the beginning of the construction of Mark I (in 1942), a technician at Harvard told Aiken that he had seen some wheels belonging to a similar machine to the one that Aiken had constructed. After some inquiry it was disclosed that these wheels belonged to Babbage's Difference Engine. This component had been presented in 1886 to Harvard, by one of Babbage's sons, on the condition that Harvard would pay the expenses for their shipment in conjunction with the 250th anniversary of Harvard's foundation [48]. It occurs to me that it was only from that event onwards that Aiken began to take an interest in Babbage. Aiken got two copies of Babbage's 1864 *Passages from the Life of a Philosopher*. Aiken got one copy from J. W. Bryce, an IBM engineer who was head of the construction team of Mark I. The other copy came from L. J. Comrie, who was in charge of the production of astronomical tables for the British Navy. Comrie visited Aiken at Harvard in May 1946, and a few months later, on an occasion of Aiken's trip to England, Comrie presented him with the copy. The challenge set by Babbage, of the difficulty of constructing the analytical engine, extended Aiken's achievement, and thus he adopted Babbage as his spiritual mentor, but only in retrospect [49]. This is further illuminated by a comparison of the introductory sections of Aiken's (1937) proposal with the joint paper that he wrote with G. Hopper in 1946, 'The Automatic Sequence Controlled Calculator—I'. Here a bibliography is provided for that historical introduction. A picture was also added of the component of Babbage's Difference Engine found at Harvard. By 1946 Aiken had made personal contact with the great-grandson of Babbage, Richard Babbage, an assistant editor of Canada's national farm magazine, *Family Herald and Weekly Star.* Aiken afforded him the honor of delivering the opening address at the First Harvard Symposium on Large Scale Digital Calculating Machinery that took place between 7th and 10th of January 1947. In an article published in *Nature* (1946), Comrie wrote 'Babbage's Dream Comes True', demonstrating clearly, in its very title, the myth that Aiken had created [50].

John Vincent Atanasoff

Although Atanasoff did develop an automatic program-controlled digital calculating machine, he did not bring it into use. Even though this is under dispute, I have decided to include it here, due to the possible later effects that, it is claimed, could have resulted from his ideas. Yet, I disregard the decision taken by Judge Earl Richard Larson in the trial Honeywell vs. Sperry Rand [51], because courtroom justice is not necessarily historical justice. Judicial aims differ sharply from historical investigations.

Atanasoff was born in 1903 in the State of New York, the first son in an initially childless family that became a big family of ten children. They were very poor and moved around. Atanasoff's father was born in SW Bulgaria in 1876. When he was a few months old a Turkish bullet grazed his head and killed his grandfather. In 1889, after two stepfathers were brought to the USA by an uncle, he narrates (Shishkov, 2001, p. 10), he was left alone at the age of 15, and somehow got through Colgate University in about 1900 with a BPh (Bachelor in Physics). His mother finished high school and normal training though school, and married. She was a most intense student and was terrifically capable in her high school mathematics, and much better than his father who had had calculus. His father left a lifelong impression on him. She and his father had trained him in a ready use of tools and science that, he claims, 'persisted throughout life, although I have been trained in theoretical physics I could easily compete with experimental physicists, and I have had experimental students to prove it.'

Atanasoff's father took an International Correspondence Course in Electrical Engineering. It became the family livelihood.

In September 1908, his mother took him to the Lyndhurst School, New Jersey. After a few months at school, his mother asked to hear him read. She did not like what she heard and said exactly this: 'I see I must teach you myself', which she did with three or four years of additional work. What his mother did was to change him from a very poor 'look and say' whole word pattern recognition reader to a rather poor phonic reader. She told him with some emphasis, 'You are still in trouble, English cannot be taught by any good method, either "look and say" or phonics, but phonics is better. Since English is not a phonic language each word that you want to use must be memorized.' This is an interesting issue, especially in an immigrant country. We can see the difficulty of people used to phonetic writing, such as the Slavic languages, including Bulgarian, compared to those used to non-phonetic writing, such as English or French. This is mentioned here as it is of later relevance when Atanasoff, in the 1970s, tried to develop a new phonetic inscription suitable for computer voice recognition.

By spring 1913 his father had decided to move to Florida because the family had lost two children and felt that a warmer climate would help the family. They stayed first with Fred, his uncle on his mother's side, during which time Atanasoff did not attend school. Only in the fall did he begin attending a local school which had only two teachers. The principal soon found that he could read and filled Atanasoff's desk with books on various scientific subjects.

Around the end of that year, Atanasoff's father found a job as an electrical engineer in a phosphate mine in a new town, Brewster, to which the family moved. It had still no school. It was the first time that the Atanasoff family had reached a higher standard of living. Only then could they afford electrical lights in their home; they purchased their first car. These were most important events in the Atanasoff family. Due to the hot weather in Florida they installed Brewster electrical fans at their home. His mother acquired an electric iron.

Atanasoff, now nine and three months old, experienced an interesting period that, he claims, 'represents a major advance in my education and scientific luck.' It was his first acquaintance with the slide-rule and logarithms. His father purchased a slide-rule by mail. He did not have time to use it because, as the Florida weather damaged 150 HP motors fast, he had to organize a repair service for them at the company where he worked. So, for the next few months, Atanasoff studied a slide-rule. He also studied logarithms, trigonometry, differential calculus, physics, chemistry, astronomy, radio, telegraphy and telephony—from two books published in England. He had access to a Monroe calculator that was the property of the company where his father worked. In a letter to me (December 1986) he wrote,

> 'I later questioned if it was a Monroe calculator but I investigated and found they had started its manufacture in 1910. My life was characterized by the fact that I thought that I could learn anything by reading and I read everything I could get my hands on.'

Atanasoff was wandering around in the office where the Monroe was stored and soon learned how to partly disassemble it without damage. He learned about all the parts and understood them. His principal source of books was his father's library. At the age of almost ten he had even a small laboratory of motors, spark coils, etc. He had some difficulties in calculating by himself simple logarithms in binary. Then, in his father's library, he found a book by J. M. Taylor, *A College Algebra* (1895). It contained a chapter on logarithmic calculations.

Atanasoff says that his mother had a prominent role in his selection of the numerical base notation in digital calculations. As a mathematics teacher who taught algebra, once she noticed the great interest in algebra that her child exhibited, she assisted him with overcoming his difficulties in calculating with logarithms in various bases; for example, the passage from the quinary (five) base notation to the natural logarithm base, and from both to the decimal base notation. His mother had a very old textbook in arithmetic—written by Horatio N. Robinson—that she had used for teaching eighth grade classes. One of the chapters carried the following heading: 'Numbers to Other Bases than Ten'. This was an unusual chapter because, among other things, it dealt with transforming numbers from other bases into the decimal base. In his letter to me, Atanasoff writes,

> 'I read this chapter and this furnished all I have had to learn on this subject to this very day. And you must realize that I introduced the base of two or the binary into computing. As I look back it is surprising that I had so much interest in computers in 1913.'

At the same time, to repeat, Atanasoff began to show interest in anything written in English literature on physics, radio, telephone, telegraphy and practical electricity. On one occasion he noticed that the electric light circuits on their porch were wrongly installed, and so he corrected the wiring, accomplishing this all in the dark. A certain book on the radio telephone treated the problem of the electrical arc that was then the only way to generate continuous radio waves. In the radios of the 1920s, then, a novelty, the frequency modulation, was obtained by a crystal. This was solid state technology and before the utilization of the thermionic tube. The book also treated the application of magnetized metal wire conductors, used since the 1950s as slow memory storage.

During his second high-school year, he decided to work on theoretical physics because he thought that physics provided the broadest view of the phenomena of nature. He used to borrow many books from the college library. As a boy he liked to read encyclopedias, apparently becoming this way aware of Babbage. In 1925 he got his Bachelor degree in Engineering from Florida State University. He studied electrical engineering there, as, so he claims, it was the closest available topic to theoretical physics.

> 'While studying electrical engineering I did not learn any electronics because this subject had not been invented. I believe when I graduated from U of Florida only two engineering schools were giving electronics courses in the US; when I got the PhD in 1930 nearly all were using that subject in their curriculum.' [Personal communication, 18th December 1986].

In September 1925 Atanasoff moved to Iowa State College, at Ames, to proceed with his Master's degree in Mathematics, obtaining it by 1928. There, in his first year of study, his fellow classmates discovered, in a certain book, statements like those he found in the above mentioned book of Horatio N. Robinson, dealing with the use of the binary base. During his studies of 1925-1928 he also became an instructor in physics and mathematics. His Master's thesis, which was of a very general nature, related to technology and to physics.

In March 1929, Atanasoff studied towards his PhD in Theoretical Physics at the University of Wisconsin. He received his PhD in July 1930. This was for him the most strenuous time of his studies, because he took courses in electro-dynamics, quantum mechanics and the mathematical theory of elastics, which he had intended to present in his PhD dissertation. He continued to show interest in electronics, in particular in vacuum tubes and their application (the terms vacuum tube, valve, thermionic tube, radio tube and alike are used here interchangeably). By then these subjects also appeared in the common publications of the era. Atanasoff claims that he read more German and French literature than English, because the scientific sources in these languages were more abundant. His PhD dissertation was on 'The Dielectric Constant of Helium', guided by John Hasbrouck Van Vleck (1899-1980), who later moved to Harvard and in 1972 was awarded the Nobel prize in physics for his work on the behavior of electrons in magnetic solids.

In 1930 Atanasoff returned to Iowa State College, later the University of Iowa, as a professor in mathematics and physics.

Atanasoff felt it necessary to gain expertise for himself in electronics, so he studied vacuum tubes from textbooks and other publications, such as *The Thermionic Vacuum Tube and its Application* (1920) of H. J. van der Bijl. He constructed several types of instruments, utilizing them in his workshop.

Atanasoff had confronted already in his PhD dissertation calculation problems, especially the search for solutions of large systems of linear algebraic equations. These he tried to achieve by use of mechanical calculating machines, in particular such as were made by Monroe, with which he had been familiar since his childhood (1913).

As a professor of mathematics and physics at Iowa State University, his interest grew in improving and developing calculating means. He felt free to do anything he desired to this effect. At the outset he tried to adapt the statistical IBM punch card equipment available at the university to his and his students' requirements, in order to calculate problems of spectrum by approximating solutions in the (1909) Rayleigh-Ritz method, that was in essence the solution of equations with many unknowns using matrices. He had started to use IBM equipment even earlier, while he was working on his PhD dissertation that obliged him to solve some partial differential equations [52]. By 1934, he had constructed, together with one of his graduate students, Lynn Hannum, an analog device, the Laplaciometer, to solve Laplace's equation in two dimensions, subject to various boundary conditions.

The Iowa State College at Ames, which by 1927 had already become a center of biometrics due to Henry Wallace's initiative and IBM assistance, had a statistical calculation laboratory called the 'Mathematics Statistical Service', the first such installation within an academic campus in the USA to utilize IBM equipment.

In an interview in 1982, Atanasoff told me that he had been aware of Babbage since his youth, when he read the 11th edition of the *Britannica* (1910-1911), and regards Babbage as the spiritual mentor of the electronic computer [53]. The *Britannica*'s 11th edition has led me to the opinion that reading it cannot make one grasp Babbage's works or have any notion or picture of it, since, unlike other editions, that specific edition makes minimal reference to Babbage's doings. Another source—of July 1984—reports that Atanasoff claims that in that period (1936) he had only a superficial knowledge of Babbage's work: he could not distinguish then whether Babbage spoke of information or of storage, or whether he had any notion of storage of information (Shishkov, 2001, p. 47). I suppose that in that period (after 1930), Atanasoff could have had some slight notion as to Boolean algebra. However, I doubt that he realized its possible application for calculation. He argues that at the outset, everything he accomplished was reached by trial and error, and only then could he gain any understanding or insight. First he dubbed the logic circuits 'mechanisms of adding and subtracting'. He felt that his knowledge and skill in electronics was insufficient and that he needed the assistance of an electrical engineer, for which he chose a talented graduate named Clifford E. Berry. Atanasoff tried to make some changes and adaptations to the IBM equipment of the university. IBM dominated the tabulating market and its personnel warned him not to make any changes in their equipment. Among the exhibits of the Honeywell vs. Sperry trial at the Charles Babbage Institute I found a copy of a letter from IBM to Iowa College from 1935 that makes such an admonition. IBM's marketing policy was renting and not selling equipment. While Aiken was on the lookout for ways to design a calculating means of greater calculating power than existed at that time, Atanasoff ceased working with IBM equipment altogether. He also pushed his students harder for a more powerful computing device. Wrestling with this problem, he began to seek a different solution.

According to his own account in an interview the following was reported:

> 'After an early dinner one particular night in the winter of 1937-1938, Atanasoff anguished in his laboratory about his failure to design a better computing device. Tormented, he did what many a frustrated man has done before him: he went out for a drink of whisky. But the nearest bar was 200 miles away in Illinois. For in those days Iowa was a dry state. Atanasoff jumped into his Ford V-8 and headed off in the bitter cold in the direction of Illinois. After few hours of 80 mph driving, Atanasoff crossed the Mississippi River near Rock Island, Illinois. He stopped at the first bar and went inside. 'I had a very heavy coat, hung it up, and sat down and ordered a drink', Atanasoff remembers. 'And as the delivery of the drink was made, I realized that I was no longer so nervous and my thoughts turned again to computing machines. 'Now I don't know why my mind worked then when it had not worked previously, but things seemed to go good and cool and quiet. During this evening in the tavern, I generated within my mind the possibility of regenerative memory... During the same evening, I gained an initial concept of what are called today 'logic circuits'.' [54].

Another source claims that the place of the tavern was Moline, and that Atanasoff had ordered two glasses of bourbon with soda. Yet, he still claims that, that very night, 'I invented in my mind the computer' [55]. Eureka! Bah, humbug!

Atanasoff spent the next few months polishing the design of his calculating device. By 1939 he was confident enough to approach the college officials with a detailed proposal seeking funds to produce 'the most powerful computing machine in existence'. It was a serious undertaking and yet, in order to carry out this project, he asked for only $650. The request was granted. Of this he allocated $450 to hire the promising Iowa State electrical engineering graduate Berry Clifford. The remaining $200 was budgeted for materials [56]. The 1930s were years of economic depression and it was difficult to finance such an undertaking from a professor's wages ($2,305 for ten months). Like Stibitz, Atanasoff built his house with his own hands.

In 1940 Atanasoff negotiated with IBM and Remington Rand to sell them his invention. The correspondence on this issue suggests that both parties adopted a policy of sitting and waiting for the other party to make the first move. For five years Atanasoff tried, with his university's assistance, to formulate a patent application for his invention, without success. By 1942 he had applied to the National Defense Research Committee (NDRC) to get the necessary support to complete his device and for the possible application of it for military use. The issue was conveyed for Norbert Wiener's examination at MIT. In January 1942, his documents were returned to him, his proposal rejected. Embittered, he abandoned the development in August 1942, even though it was already in its final stages, and joined, together with several of his graduate students, the Acoustics Department of the US Navy Ordnance Laboratory in Maryland. One of those who recommended him for the job was Norbert Wiener. After abandoning the development of his device in August 1942, Atanasoff never returned to work in the Navy. After the war, he was asked to head certain computer projects for the Navy. Aiken invited Atanasoff, in a letter of November 7, 1946, to give a lecture on storage means in the First Harvard Symposium on Large Scale Digital Machinery (held on January 7-10, 1947). I find this invitation of Aiken something of a surprise: it is not clear to me what the reasons for this invitation were. As Aiken was also in the Navy, they may have met there.

In the 1950s and the 1960s, confrontations mounted on the issue of patent rights of electronic computing devices—computers. The legal councilors of IBM and Honeywell approached Atanasoff, and later also Berry, to come and claim their rights as the inventors of the electronic computer. To repeat, this makes for a digression far beyond the scope of the present study.

I end this part of Atanasoff's biography with two citations from his letter to me, dated 18th December 1986. The first section refers to him as a 'computer pioneer':

> 'Correction: I am 'the' not 'one of the' pioneers. I changed computing from Babbage to the modern structure. My machine was more like the modern machine than ENIAC although Burks proves I invented ENIAC.'

The second section is from the third page of his letter:

> 'Thinking over my history for you has led me to remember that I get results by arm-chair thinking; I am a theoretical physicist. Nevertheless, I am easy at experimentation and have directed at least five graduate students in experimental theses and perhaps I do not think there is any difference. But perhaps I should also say that in computing I have planned the machine and made drawings which were largely executed by my assistant Clifford Berry.'

John Adam Presper Eckert Jr. (1919-1995)

Eckert was born in Philadelphia in 1919. Very little is known about his childhood. Interviews with him, when he agreed to give them, were usually technical in nature. He received all his academic degrees from the Moore School of Electrical Engineering at the University of Pennsylvania. He then specialized in electronic pulses, radar and the retrieval of pulses for memory storage. In 1941 he obtained a television patent for a light modulator in ultra sound waves. He has been considered as the most brilliant engineer in that *milieu*. He was involved in conducting several courses connected with the preparation of academic staff as emergency reserves in case of war. He was also involved in several military electronic systems development projects which were carried out as a joint venture with MIT. He worked on the Differential Analyzer at the Moore School, which was constructed according to the design of Vannevar Bush of MIT. He made several changes to that analyzer and helped to convert certain mechanical components into electronic ones. He received his PhD in 1943, under Mauchly's guidance. Later, he and Mauchly were co-inventors of the ENIAC patent, partners of a joint firm and partook in a friendship that lasted almost forty years until Mauchly's death. In the period 1943-1946, Eckert was appointed as the chief engineer to the ENIAC project at the Moore School. It was Eckert who encouraged Mauchly to have confidence in the reliability of a wide and large scale application of vacuum tubes, which most tube experts deemed impractical. Eckert found a very simple way to bypass and overcome the limitation of the reliability and life expectancy of the vacuum tubes on the one hand, and how to detect and remedy malfunctions in a device containing such vast quantities of tubes on the other. In its initial design, ENIAC was supposed to have some five thousand tubes. Once the feasibility of such a device was shown, the Army's demands from the designers extended. Gradually the number of tubes rose to eighteen thousand. In those days the greatest number of tubes in any single electronic device, such as radar, was in the region of several hundred tubes at the most. Eckert proposed to overcome the shortcomings of the vacuum tubes and other electronic components by utilizing a standard type of tube in all the circuits and to reduce by half the standard working load in the tubes and other components. As for the problems of detecting and remedying malfunctions, he proposed applying a modular construction approach, enabling the easy replacement of a complete module, which was then a novelty. Today it is very common in the computer industry, as it is in other industries.

Like Mauchly, Eckert was not aware of the works of Babbage or of Turing [57]. But he was familiar with electronic counting circuits developed by others. There are sufficient grounds to assume that, like Mauchly, he knew about the 1919 electronic trigger circuit of Eccles and Jordan. During the period 1935-1941, Mauchly certainly and Eckert most likely read in the *Review of Scientific Instruments* about counting means based on thyratrons (gas-filled tubes used as high-power electrical switches and controlled rectifiers), the much more advanced designs and developments than that of Eccles and Jordan, not to mention the electronic counters for radiation.

Despite the advantage of the Eccles-Jordan device that was much faster and based on binary notation technology, Eckert adopted and used in ENIAC the tube in a decimal calculating and storage element—the counting ring. That is an imitation of the wheel as a counting-calculating and storage component with electronic pulse technology that is by nature discrete and can fit binary notation with ease. Electronic counting means, common during the early 1940s, utilized various base notations. Some elementary particle counters used binary notation; others used rings of tubes that counted in decimals by means of four binary flip-flops of seven or more tubes. The calculating circuit designed by Eckert and the ENIAC team used ten tubes to represent a single decimal digit. Such a ring of tubes was an imitation of the ten-tooth calculating wheel in the cogwheel gear mechanism.

Eckert, like Mauchly, had been aware of the work of Stibitz and his colleagues at Bell, as well as the development of counting means at MIT, RCA and NCR.

In 1953, Eckert claimed that he had not apply the binary notation or the integration of binary decimal notation in ENIAC because the technology was then not sufficiently reliable and because

> 'It required stable resistors, which were then much more expensive than they are now' [58].

In 1976 Mauchly and Eckert claimed that, due to the application of the decimal code notation in ENIAC, they had to use a greater number of tubes than was required in binary devices utilizing the decimal notation based on the flip-flop element [59]. Yet both proposal reports submitted by the Moore School to the Ballistic Research Laboratory in April 1943 did not neglect the application of binary notation in their proposed devices [60].

Clifford Edward Berry (1918-1963)

The biography of Berry's childhood and youth is somewhat vague and fuzzy, and was unknown until a little after his death. In October 1986, his wife Jean published an article about him in the *Annals of the History of Computing* that contains a sentence or two on his youth. The literature of the history of computer usually mentions Berry with Atanasoff. It was Atanasoff who saw to it that Berry should be given a proper place in his work and elevated his assistant's contribution in the development of their device at Iowa State College undertaken during the years 1939-1942.

Berry graduated from high school in Marengo, Iowa in 1934 at the age of 16. He had a straight A average and was class valedictorian. Because of his young age, his family suggested that he should wait a year before starting college. He spent that year taking more science courses and working on his ham radio setup. For financial reasons, his widowed mother moved to Ames so that all four children could attend Iowa State College. Berry earned money for college tuition by working at Gulliver Electric. In spite of his outside work he maintained an extremely high grade average, and was elected to four honorary fraternities. In his junior year he was given a special award for achieving the highest scholastic record in the Department of Electrical Engineering. He graduated in 1939 and began work on his graduate degree in physics and mathematics in parallel, as fate would have it, with concurrent work being carried out on Atanasoff's calculating device. Atanasoff felt that

> 'I should choose an electrical engineer, since most students entering graduate work in physics did not have mechanical or electrical skill. From my point of view, he had to be a very special engineering student.' [61].

Atanasoff turned to Harold Anderson, a professor of electric engineering (probably the dean of the department of engineering), to find a graduate student from the engineering department who would be his assistant in the design of the calculating device. Anderson recommended Berry without hesitation, on the condition that Berry found an interest in calculating devices. Berry received his Master's degree in Physics in 1941. His thesis was carried out under the guidance of Atanasoff. It rested on his main contribution to the design of Atanasoff's device: 'Design of Electrical Data Recording and Reading Mechanism'. This mechanism was supposed to punch holes in a paper card by means of an electric spark at the rate of sixty perforations per second, a speed that in those days was considered unfeasible. In November 1941 Berry joined the Atanasoff team; Berry's girlfriend, Jean Marta Reed (later his wife) was a secretary for Atanasoff's missile project working in unsuspected parallel in Berry's calculating device project. At the end of June 1942, with the abandonment of the calculating device project at Iowa College, Berry gave up once and for all the digital approach to calculating devices and diverted his attention to the trend of analog calculating devices. He and his newly wedded wife (30th May 1942) left Ames at the end of June 1942 and moved to Pasadena, California. There he found work at the Consolidated Engineering Corporation and started his doctoral studies. Later on, this company merged with the Burroughs computer company. In 1945 Berry developed for that company an analog calculating device termed '30-103', designed to solve large systems of linear equations simultaneously. It was originally designed for simultaneous calculations in mass spectroscopy. It was only by 1948 that Berry had the leisure of being able to complete his doctoral dissertation. It dealt with spectroscopy; in this *milieu* that he gained worldwide fame.

On June 10, 1951 Berry received a patent for the '30-103'. He applied for forty-seven patents in all, forty-six of which were in spectroscopy; of these, thirty were approved. In 1963 he moved to New York to work at Vacuum Electronics. On 10th October he was found dead in his apartment with a nylon bag covering his head. There are several versions of the causes of his death. For example, Atanasoff claims that he was murdered. The coroner ruled it a suicide. Is it likely that the mystery of Berry's death might somehow have a bearing upon the history of computers? Alas, that exceeds the scope of the present study, requiring, as it does, deeper and extensive investigation all by itself.

After Berry's unexpected death, Atanasoff decided to make a perpetual tribute to his late student and assistant by naming the device they developed as 'the Atanasoff-Berry Computer' (ABC). In this R. K. Richards preceded him with the 1966 publication of his book, *Electronic Digital Systems*. (See below.) In the 1940 issue of Iowa State College's Electrical Department's newsletter EE News, Berry wrote the following:

> 'I am still working on the calculating machine [the prototype had been completed in 1939] and we can see the end in view, though some months off.'

Jean Berry, his widow, had discovered a letter from 12th July 1963 from Berry to Dr. Richards of Iowa State University. It is a reply to questions presented by Richards in a previous letter. The answers in Berry's letter are given only from memory, because Berry had forgotten where he placed his personal notes, reports and the patent applications:

> 'The machine was designed for a single purpose, namely to solve large sets of linear simultaneous algebraic equations (up to 30x30) ... It used binary arithmetic internally ... The maximum time required, in the worst possible case, for the machine to eliminate a variable between two equations, was 90 seconds; the average was much less. Within the machine were two storage units ... Design and construction began in September, 1939 when I began my graduate work. It is amusing to recall that Prof. Atanasoff instructed me to build a framework for the machine during the first month before we had any real idea of what was going to go in the machine. As a result, the machine "grew" as the work progressed, rather than being first designed and then constructed. ... The only major element that was not completed when work was stopped in the middle of 1942 was the reading circuits for the binary cards ... Prof. Atanasoff had thought about computing machines for several years ... I am sure he was aware of the early work in the field, and I recall that we were at least aware of Aiken's "relay" computer although we may not have known much about it.' [62].

Jean, Berry's widow, has corresponded with Richards and other people involved in the ABC project. This correspondence took place only after Berry's death (1963) and is therefore better treated with caution. So, for instance, Richards wrote to Jean confirming that he was writing a book on computers (in 1963), and he mentions Berry in connection with Atanasoff:

> '...in as much as Dr. Atanasoff had told me on the telephone that many ideas in the machine, as well as the actual construction, should be credited to Cliff Berry' (Richards 1966).

The introduction of Richards' book says:

> 'The ancestry of all electronic digital systems appears to be traceable to a computer which will here be called the Atanasoff-Berry computer [ABC]. This computer was built during the period from about 1939 to 1942.'

It seems to me that Berry was not aware of Babbage; there is no direct lineage at all. It is also doubtful that he had heard of Turing's work. However, the above reference to Aiken sheds some light upon Atanasoff's knowledge of Aiken's work, though Atanasoff himself never raised this possibility.

Remark:

Iowa State University, and even the government of Bulgaria, whence Atanasoff's parents came, were very proud that Atanasoff, and through him also Berry, were declared the inventors of the first electronic, automatic, digital computer after years of legal proceedings in the courts (Minnesota 1969-1973). Without entering into confusing statements from within the verdict, by court decree, Mauchly and Eckert were deprived of the ENIAC patent, because the judge was of the opinion that the invention of the ENIAC computer derived from someone known as Dr. Atanasoff. Given all the discrepancies and uncertainty in the research, we may view the resolution of the honorable judge as still under dispute. To put it bluntly, the judge's verdict is unacceptable as it stands since Goldstine, Burks and others, who also had claims to be recognized as co-inventors of ENIAC, were in disagreement with Mauchly and Eckert—due to a number of motives, issues of prestige, practicalities, clashes of egos and other reasons, that need no further recapitulation. Suffice for now to say that they have seen to it that the role of Atanasoff and Berry has been elevated in order to have Mauchly's and Eckert's position demoted.

The above is intended merely to emphasize the problematic nature of the sources (the likes of Richards and of Jean, Berry's wife, etc.), and their relevance to the debate concerning the relationships between Atanasoff, Berry and Mauchly after July 1941, resulting from the crucial meeting between Atanasoff and Mauchly.

To further stress the point as to how ego matter may divert judgment in such matters, I present here the example of Professor Arthur Burks. Professor Burks, whom I had the opportunity to meet personally, is a pleasant, polite, tall, lean and good-looking person, and dare I even say, a princely personage. Burks made an indelible impression on me during our meeting as a most honest, straight and considerate person, a gracious host, a pleasant speaker and a wonderful listener. All this notwithstanding, I found it hard to deny that Burks was badly hurt; he believes that he deserves to be recognized, partially, or to a certain defined extent, as a co-inventor of ENIAC. In his view Mauchly and Eckert deserved to share with him and with others the honor and dignity, if not materially in money or royalties, then at least a place in history. This injury is hard to bear. Obviously, many of the ENIAC team-members contributed ideas and more during their joint effort on ENIAC. Nevertheless, equally obviously, it was Mauchly who originated the project. The struggle now is how this or that person will be remembered in history. This is a ruthless and bitter battle, into which even such marvelous people of the caliber of Burks are dragged innocently and viscerally. Knowing the person and the historical background, it seems to me that, in the case of Burks, there is nothing strange in his demand. However, in other cases (see Appendix B, 'The Borrowed Fame'), others have been active in their considerations, and these people went up against Mauchly and Eckert in the very early stages, as early as in 1945. And, in my opinion, this opposition has to do with other motives, derived from conscious and pragmatic considerations about personal profit and prestige, if not more than that.

The United Kingdom

Our discourse on events in the UK converges on a group of individuals involved to some extent in the development of code deciphering devices. The difficulty here in speaking about specific individuals is the lack of official sources of information due to the Official Secrets Act. This veil of secrecy was lifted only in 2006, after the history of their development became sufficiently settled to be the received myth. Hence, anything presented here should be considered with special care.

C. E. Wynn-Williams (1903-1979)

Wynn-Williams was born in Swansea, Wales, in 1903 and died in 1979. In his childhood he studied at Grove Park Grammar School in Wrexham, Wales. In 1920 he began his studies at University College of Bangor, North Wales, on a scholarship and the counties prize in mathematics. In 1922, he received there BSc with distinction and a Master's degree in 1924. In 1925 he moved to the Cavendish Laboratory in Cambridge where he worked in physics research under the guidance of Rutherford, receiving his PhD in 1929. At the same time, he also began further BSc studies in London, which he completed with distinction as well.

He is considered a pioneer in the utilization of thermionic tubes of various types for measurement, counting and calculating means for radiation and nuclear physics.

After 1931 he started to develop electronic counters for elementary particles, mainly for the measurement of x-rays and their photo-electric effects. His major contribution was the construction of a valve amplifier for tracing discrete particles while sheltering them against external influences. Later on, he designed counting circuits in binary notation. In 1942, he worked at the TRE (Telecommunications Research Establishment). There he was engaged also in the development of radar. He was summoned to Bletchley Park to help to find a solution for speeding up the decoding process. He was among the designers of the 'Robinson' decoding device that comprised electronic logic circuits and photo-electric readers. It was an important step towards the appearance of the Colossus [63].

Alan Mathison Turing (1912-1954)

Several biographies have been written on Turing. The first, *Alan M. Turing*, was written by his mother Sara in 1951. The second was written by Andrew Hodges, titled *Alan Turing: the Enigma* (1983). Hodges' book concentrates on the homosexual aspect of Turing's life. It is an excellent work, also treating other aspects of Turing's life profoundly, including his contribution to the history of computers. Particular attention is paid there to Turing's boyhood. Among the papers given by his mother to the King's College Library Archives at Cambridge are manuscripts, letters and other documents that Dr. Robin Gandy was trying to edit since the early 1970s. Gandy was one of the very few doctoral students whom Turing supervised. He died in 1995 having published three out of the four volumes of Turing's collected works. The fourth volume was completed by his colleague C. E. M. (Mike) Yates in 2001: *Mathematical Logic*, eds. R. O. Gandy and C. E. M. Yates (Andrew Hodges, *The Alan Turing Bibliography*).

Turing had a great interest in inventing things. For example, Turing wrote a letter on April 1, 1923 with a fountain-pen that he had invented; it includes a diagram. In another letter he gives an account of an ink he created. In other letters of that period he describes a new typewriter, an amphibious bicycle, and a bicycle-powered generator.

He spent his youth in a boarding school in Sherborn, where he experienced a profoundly traumatic event: the untimely death of his best friend Christopher from tuberculosis.

After his graduation from Sherborn School in 1931, Turing commenced his study of mathematics at King's College, Cambridge. In 1935, during a course in mathematical logic conducted by Max Newman (on Newman, see separate section), Turing was introduced to the 'mechanical process' in logic, an algorithm or a fixed process for decision-making in performing logical or mathematical operations. The direct outcome of this idea was his famous work from 1936, 'On Computable Numbers', that he accomplished independently and without any direction or guidance from his professors. Between 1936 and 1938, he studied at Princeton University under the guidance of the distinguished mathematical logician Alonzo Church.

As a member of Cambridge University, he might have become aware of Babbage, also a Cambridge man and a holder of the most prestigious Lucasian Chair of Mathematics for eleven successive years (from 1828). In the lectures given by Newman, Turing heard of the works of Hilbert, Russell and Whitehead and Gödel. At Princeton, during his free time in the workshop of the Faculty of Physics, Turing constructed an electromagnetic, binary multiplier and became interested in electronics. During the journey back to the UK in 1938, he delved deeply into a popular electronics booklet. Even before the publication of his work on the 'computable numbers', Turing tried in Cambridge to construct a prototype of a mechanical calculating device to calculate various values of the Riemann Zeta function. His PhD dissertation was on the 'Systems of Logic Based on Ordinals'. He received the PhD in Princeton in 1938 [64].

Michael Woodger's 1958 paper 'The history and present use of digital computers at the National Physical Laboratory' reports on Turing's interest in designing a computing machine. Woodger worked with Turing in 1946 at the National Physics Laboratory (NPL) on the ACE (discussed further on). In Princeton, just before returning to the UK, Turing discussed with von Neumann the possibility of constructing a high-speed automatic calculating device that uses radio tubes for relays. In Woodger's words,

> 'Both men were experts in the field of mathematical logic and while the subject had little direct bearing on the design of such machines it enabled them to see at once how the general problems of control and manipulation of sequences of binary digits might be effected.' [65].

This is a plausible story. Nevertheless, I doubt that it is true, as these two were extremely different individuals. Many have desired to detect some sort of relationship between them, but the evidence indicates that no meeting between them ever happened. Even if it was theoretically possible in time and space for such a meeting, then it might have unpredictable consequences on the future of the history of the computer, as the Earl of Halsbury has suggested (1959). Pamela McCorduck (1979) raises also the issue of such a possible meeting having occurred very close to Turing's arrival to the USA in November 1942 [66]. Considering the available information, I am still of the opinion that had such a meeting taken place, then it wound have included no discussion about computers. Von Neumann's interest in calculating machines began only towards the end of 1942 or at the beginning of 1943. The paths of von Neumann and Turing might have crossed and intersected. Yet, according to the above scholars, the discussions were of a different sort of problem than computers. Even during his stay at Bell Labs, as Stibitz indicates, Turing was indifferent to the ballistic computer. And it is clear that he was sent for a purpose different than calculating machines. He was then interested in means of cloaking and camouflage. To repeat, Turing and von Neumann were of different characters and personalities. Turing understood von Neumann. While in Princeton, Turing refused the tempting offer to be von Neumann's assistant, a great honor for any young graduate. Instead he broke off all contact with von Neumann and returned home.

In September 1938, Turing joined the British Foreign Office's Decoding Center at Bletchley Park in the vicinity of London. It seems that he was behind the logic design of an electro-magnetic decoding device termed the 'Bomb', and among others projects devised a specific new statistical technique to significantly reduce probabilities while carrying out the decoding process. At the end of 1942 he was sent urgently to the USA for several months to test the reliability of means of voice telecommunication encoding. These were needed for the verbal coordination of strategic decisions and war plans between Roosevelt and Churchill. However, another version, unreliable in my opinion, claims that he went to the USA to participate in calculations connected with nuclear weapons. This would coincide with the possible common interest with von Neumann in an electronic calculating device. But this is merely wishful thinking in order to connect the two. At that time Turing worked at Bell Laboratories with Claude Shannon, the originator of information theory (1948), himself an expert in cryptography. During that time, Stibitz introduced the Bell MODEL III (ballistic computer), but to Stibitz's disappointment, Turing showed no interest. Until the end of the war, Turing remained involved in binary voice encoding and developed acoustic and other means of storing information.

In June 1945 he went to Germany and Austria as a part of a scientific military team for the examination of the developments made there during the war, including the interrogation of various German and Austria experts. In October 1945 he joined the NPL to work on the design and development of the ACE (Automatic Electronic Engine). His designs are distinguished as the most economical design in hardware and its accompanying software. From 1947 until his tragic death in 1954, Turing worked on Manchester University's computer project.

Maxwell Herman Alexander Newman (1897-1984)

The founding Professor of Mathematical Logic and Topology at Cambridge, Newman is considered one of the most important mathematicians of his time. The first to start modern topology in the UK, Newman was Turing's teacher and tutor in the spring of 1935. Newman joined Bletchley Park in summer 1942. He established there what has since become known as the 'Newmanry', a team in search of methods for speeding up decoding. To this end he adopted a statistical approach developed by Turing in 1941-1942. From information gained in autumn 1942 he reached the conclusion that only electronics could give the proper solution of decoding in real time (at the risk of anachronism; I do not know when this term entered common use). Thus arose the idea to design the 'Robinson' (see also above, on Wynn-Williams), a device having electronic logic circuits and photo-electric punch-paper readers. The only difficulty with the Robinson, during the development of several prototypes between 1942 and 1943, was that the punch paper tape caught fire while rotating at a speed of photo-electric reading that was much higher than that of the electro-magnetic reading in the Bombs. Under Newman's direction the team developed the 'Colossus', the first totally electronic device, apparently the first of its type in the world, the details of which were not officially disclosed, being still under protection of the Official Secrets Act, before the literature on it that I contest became traditional [67].

After the end of the War, Newman contributed to the development of MADM (sometimes called MADAM), the first electronic automatic digital computer designed and constructed at the University of Manchester, UK. It was Newman who brought Turing to the University of Manchester from the NPL in 1948 to take part in the development of this computer.

Thomas H. Flowers (1905-1998)

Flowers' main occupation was communications and the transfer of signals over long distances. He had very great experience in electronics. In 1931, he was among the first to try to use vacuum tubes in telephone switching, and by 1935, a practical result of that project was already produced with the automatic dialing system.

He conceived the idea of storing the information of the punch paper tapes used in the Bomb and the Colossus in electronic logic circuits, which could be considered today as data imprinted in hardware (ROM—Read Only Memory), and thereby of obtaining data reading speeds twenty thousand times faster than those in the Bomb [68].

During World War II Germany used machine-enciphered teleprinter messages (Enigma). At Bletchley Park, means were developed to decode them by raising considerably the speed of electromagnetic and electronics processes. The first electronic machine made for this purpose was Colossus that went into service in December 1943 and that did a very valuable work. It is claimed that Colossus had most if not all of the essential features of a modem computer, though it was programmed by hard-wired function units selected and interconnected by switches that mathematician-programmers controlled.

Chapter Three Summary

In summing up the narrative on the personal and the group portrait of the developers of the automatic program-controlled digital calculating machines, the following historical picture emerges: the various developers acted independently and probably shared no motive. Moreover, the individual biographies indicate and establish that the development of the automatic program-controlled digital calculating machines was mostly undertaken individually and in reciprocal ignorance, and in no continuity with the forgotten calculating means developed earlier. Historiographically, it becomes clear that the linkage to past traditions is a part of a myth created by some of the developers. For instance, Atanasoff, Zuse and in particular Aiken adopted Babbage as their spiritual mentor, but only in retrospect. Yet, when writing their memoirs or publications concerning the development of their devices, intentionally or unintentionally they gave the impression of prior familiarity and influence that just was not there. Yet the idea of a linear chronological continuity tradition in the history of the computer was absorbed and fostered very easily by the traditional writers of the history of computing. There is no primary research or new field research to speak of; and the secondary research, meaning scholarship and analysis of existing primary research, is vastly inadequate.

The 'professional skill' or 'knowledge' of the developers of the automatic program-controlled digital calculating machines on what occurred in the past in the *milieu* of calculating devices consists mostly of deliberations or surveys easily available in encyclopedia articles or in catalogs of calculating devices. When one compares the autobiography of Zuse (both editions), the interviews given by him and his written sources of the 1930s and 1940, it is easy to see the emphasis on how his developments were made independently and in isolation from all that happened with other developers in that era or in the past. Yet, when Zuse wrote his historical survey *The Outline of a Computer—Development from Mechanics to Electronics*, he provided an account of the development of the computer in the linear tradition, tracing it back to the calculating devices of Schickard, Pascal, etc. [69], all the way back to Babbage whom he hails as *the* modem computer pioneer. During my discussion with Zuse I pointed out to him this contradiction—between his claim that he had developed his devices in ignorance of other, previous or parallel developments, and his account in *The Outline of a Computer—Development from Mechanics to Electronics*. He replied, 'probably this is the way I have been taught to write history, one should start at a certain place.' This is precisely the issue. Why begin where he did, somewhere in the past at such a point in time as that of Schickard? I find it somewhat arbitrary and derived from prejudice, exactly as Zuse told me. We are trained to see history as a linear chronology even in events that do not necessarily follow a trend, and thereby we miss the karmic or even dharmic confluence of favorable circumstances toward whatever outcome.

In my similar discussion with Dr. Herman Goldstine at his office at the American Philosophical Society, I asked him about his opinion on the way the history of the computer is written. He answered that he was 'not satisfied with what has been written'. As to what he was not pleased about with the writing of it, how did he want it written instead, and specifically whether linear continuity with the past pleases him, he replied in validation of my own contention: the development of the computer came to pass in discontinuity to what has happened in the past. However, asked to reconcile our view with his book, *The Computer—from Pascal to von Neumann*, Goldstine replied that at that time he was interested in calculating devices and he included them in his book. Once more, as previously with Zuse, Goldstine and all the original members of the ENIAC team claim unequivocally that the development of ENIAC came to pass entirely in ignorance of the works of Babbage, Turing, Hilbert or Russell. But when Goldstine or other members of the team proffered any historical or biographical account of their work, somehow those very claims of independent development faded away and became indistinct. Goldstine remained blithely unaware of the contradiction.

It seems to me that the writings of Goldstine, Zuse, Aiken and others illustrate the depth of penetration of the linear continuous tradition in the writing of history, causing such marked distortions in the judgment and description of events, in contrast to the evidence and information at their disposal. That is to say, they were expected to write about their deeds and they did write about their deeds. And they could not disconnect these deeds from what has happened in the mythic past. Therefore, they were unable to observe the contradiction between their claims for independent and separate developments and between what happened in the past, and their accounts of the past on the other. The damage caused by this historiographical lapse, particularly that of Goldstine, is in how other people accord authoritative special importance to this sort of writing, later quoted as primary sources. It contributes, intentionally or unintentionally, to the creation of a myth that they did not intend and that causes the distortion of the history of computers. It only strengthens my claim that people often blithely contradict themselves.

Most of these developers had their background either in technical engineering, physics, or mathematics, either alone or in integration. Their academic training was broad and most had doctorates. They were a different sort of ‘inventor’ than their predecessors who lacked formal academic education, like Watt, Boole Faraday, Heaviside or Edison, and who acted outside the academic establishment and independently of it. It was a group of young academics, mostly in their twenties, all below thirty-five years of age, coming from different walks of life and professional backgrounds, and who were looking to find a better way to perform large scale, complex and tiresome calculations. Yet, their development of automatic program-controlled digital calculating machines did not result from special or unique calculating needs or the needs of the era, nor were they compelled to invent. On the contrary, for unique needs, unique solutions of devices were provided. For example, the calculating devices of the 1930s were of sufficient accuracy for engineering needs and all other professions. The common small slide-rule provided adequate solutions. Analog devices until 1945 (the date ENIAC was activated) were faster than the digital devices discussed here. Therefore, even the factor of speed did not play any decisive role or influence in the development of automatic program-controlled digital calculating machines. The claim is sheer vanity that in the 1930s the need to solve more complicated calculations, etc. brought to bear the development of these devices.

To repeat, most of the developers had some practical and theoretical knowledge in electricity, electronics and mathematics, because most of them were graduates of technical higher education schools. From the beginning of their idea until its crystallization and feasibility, they acted on their own and independently, without help. Later, inventors who were mathematicians or physicists, they recruited experts in electricity, electronics or communications. For example, Zuse and Schreyer; Stibitz and Sam Williams; Mauchly and Eckert; Atanasoff and Berry; Aiken and the IBM technical engineering team; and Turing and the experts from the British Post Office and other communications establishments.

Zuse graduated as a construction engineer, and his main occupation was static and kinetic calculations with interrelations with physics. His know-how in electricity was limited to the theoretical level. Atanasoff, Mauchly, Eckert and Aiken studied electricity or even electrical engineering, and like Stibitz they possessed a broad background in physics. Stibitz was a qualified mathematician who had great practical interest in electricity and electronics as a hobby and as a means of financial support. Aiken was employed for many years as a telephone operator; he was thus familiar with line communication and telephone exchanges. Turing may be an exception. He was a theoretical scholar trying by himself, as an autodidact, to solve practical problems. Turing's development of voice encoding, the binary multiplier and other practical inventions demonstrate his practical ability, without having had any sort of formal technical education. Yet, once Turing discovered the concept in principle or found the practical breakthrough, he lost interest in the topic and moved on to occupy himself elsewhere.

As a generality, once the developers crystallized their ideas, they began to research the relevant work of others. As to the utilization of those sources once discovered, here the pattern varies among the various developers. Some adopted ideas or practical developments by others; some ignored them.

To repeat, 'the invention of the computer' is a controversial issue because it is hard to tell who invented what. These people implemented and integrated in their devices a wide diversity of ideas and technologies. Hence, it preferable to use the term 'development of the computer' in lieu of 'the invention of the computer', (See Appendix A, 'The development of the term and concept of computer'.)

Still, the individual and collective biographical portraits of the developers of these devices at first explicitly indicates they had no common unique or particular program; nevertheless, it might be possible to trace a certain common background between the various developers. According to TRIZ, the celebrated Russian theory of inventive problem-solving, knowledge and techniques of any kind, transferred cross-discipline, are most valuable, only second to actual new discoveries. And in the 1930s, there was a greater interface between the domains of physics, engineering and mathematics. Professional expertise was not as extremely exaggerated as it is nowadays and the crossings and distinctions between the disciplines were not as rigid as they are today. Moreover, I can conclude that the automatic program-controlled digital calculating machine is an example of one of the most meaningful developments of this century that was still developed by independent developers. These developers were distinguished by their high formal academic education and differ from the famous inventors of the 19th century and the beginning of the 20th century, who were autodidacts who typically lacked any such formal education.

As for a common program guiding the development of these automatic program-controlled digital calculating machines, it is apparently possible to view this as Russell's and Whitehead's *Principia Mathematica*, which at least some of the developers, such as Turing and Stibitz, were familiar with: it is considered a very difficult book for unaided study. If this claim is indeed correct, we may naturally also argue that those developments have derived from Hilbert's program as well, because we have to see Russell and Whitehead in conjunction with Hilbert. On the other hand, if it is so, how can one explain the appearance of the Analytical Engine of Babbage, which had all the ideas and components included in the automatic program-controlled digital calculating machines almost one hundred years (1834) before the program of Hilbert, Russell and Whitehead or even Peano? Is it plausible that Babbage, and even earlier Leibniz, as well as the developers of the 1935-1945 period treated information and data in a different manner than what has been customary, instead taking information as a concrete commodity (entity) or resource? Did they realize that they were acting on substantial entities and not necessarily on abstract numerals, as was customary in the conventional calculating means? Indeed, the formation of a tradition to represent quantitative entities had already been initiated in the 14th century. And it was typical until the 17th century to conceive that mathematics was a language with its own syntax. Nevertheless, that information in general and not just information of mathematical entities could be expressed in a formal language and by digital syntax was a novelty of the 19th century, introduced by George Boole, though Leibniz referred to it earlier. Information can be manipulated, and in the broadest sense this is a result of Hilbert's program and the works of Gödel, Church, Post, and

Turing (discussed in detail in Part I). Thus, the analysis of the biographical portraits of the developers verifies what is written in Part I: that mathematical logic had no influence whatsoever on the design and development of these devices.

Also herein stands refuted the hypothesis that these developers acted according to some preset ideological program or pattern. Hence, these claims are misleading and deserve rejection.

CHAPTER FOUR

'LOOKED FOR THE ASSES AND FOUND THE KINGDOM'

Introduction

In this chapter the debate will focus on the questions: why did the developers do what they did; what were their motivations; and what is the relation between their education, deeds and the formalization of mathematics and the appearance of the automatic program-controlled digital calculating machines?

My central claim is as entitled at the heading of this chapter. These developers are like King Saul, sent forth to find his father's lost asses but who found instead the kingdom, being chosen and anointed by the prophet Samuel as the first king of Israel. The automatic program-controlled digital calculating machines came upon us as a complete surprise, like dry lightning. These devices differed from anything previously known in the calculating-means *milieu,* and their performance and capabilities surprised and shocked not only others, but the original developers as well. We have probably not yet recovered from this shock. In a way this is also the view of E. W. Dijkstra:

> 'At the heart of my explanation lies the thesis that when, now four decades ago, the electronic computer was sprung on us, we were not ready for it and that—people and computers being what they are—widespread confusion was unavoidable. By far the most common way in which we deal with something new is by trying to relate the novelty to what is familiar from the past experience.... As long as history evolves along smooth lines, we get away with this technique, but that technique breaks down whenever we are suddenly faced with something so radically different from what we have experienced before.... It is beyond the abilities of those—and they are the majority—for whom continuous evolution is the only paradigm of history, unable to cope with discontinuity, they cannot see it and will deny it when faced. But such radical novelties are precisely the things technology can confront us with. The automatic computer was one of them.' [1].

Now, most historians of the computer will tend to employ common terms such as 'computer revolution' and the like. Yet, what is a revolution if not a radical change or novelty occurring in a very short time? Or maybe not quite so short a time, as in this case. Yet, to reiterate, such is the capacity for blithe self-contradiction.

This chapter is an account of the events, as best as we can know of them, leading to the development of those devices, from known sources. I must admit to a consciousness of the calculated risk, given the historical uncertainty. We do not have and probably never will have the information on the events as they occurred. Nevertheless, the answer to the question set above enables me to delve deeply into the details of the events themselves that led to the development of the automatic program-controlled digital calculating machines, within the boundaries that I have set earlier.

What were, then, those events that occurred in the period 1935-1945 that are tied with the development of the automatic program-controlled digital calculating machines?

My starting point is set as the year 1935—arbitrarily, but this is very close to the period when these automatic program-controlled digital calculating machines emerged. Before 1935 there were no such calculating devices that presented all the properties of the automatic program-controlled digital calculating machines. Yet they existed after 1945, and there is a specific, explicit and unique definition and characterization for them. The problem facing us now is, which type of events are we to consider and what criteria are we to adopt in order to determine which of these events are relevant to the story and which are irrelevant to it? At this stage I will refer to those events that indicate a direct link between a certain event and the appearance of a particular automatic program-controlled digital calculating machine. Yet I am cautious with the use of such terminology as linkage, connection, relationship, interrelation, and so on, since an unlimited number of connections among events is always possible. This can be paralytic. And if we seek events that are indirectly connected to the appearance of those devices, then this challenges the common assumption that the answer to our question is to be found in the events as they occurred. Perhaps both types of events deserve consideration, the direct and the indirect. Then, what is the right criterion for the indirectly relevant events, and how we will know if they have been effective and to what extent? If we adopt this approach, we may find ourselves in an endless regress that contributes nothing to the explanation of the events we want explained. Instead, we better concentrate on the events that are linked with the development of the automatic program-controlled digital calculating machines in the period of after 1935.

Let us begin with Germany. There the first mechanical and electro-mechanical device was developed. Then we will proceed to the UK, where the first practical electronic device was developed. And we will conclude in the USA, where several such developments occurred in parallel.

Germany: It all began with statistical calculations

Zuse, *From Mechanical Reckoning Process* to automatic mechanization of the matrix calculations process

First let us clarify the term ‘mechanical reckoning-calculating process’. In the 1930s, at least in mathematics, this referred to any mental calculating technique that follows a fixed procedure or algorithm. Namely, it is the solution of problems by a constant patterns (formulas), in which data are set. Alternatively, ‘mechanized-calculating’ means here the execution of a calculating procedure by means of a device or machine.

In 1932 in Germany, Konrad Zuse was a student and a young construction engineer at Henschel, a leading producer of locomotives who also turned into an aircraft producer with the rise of the Nazi regime. At the age of 24, he was looking for a method to dispense with static and dynamic calculations of the strength of materials, insofar as the calculation of loads and stresses in a machine—or in building construction—belonged to practical and applied mathematics. In the analysis of a stress or load there is some considerable difficulty in treating cases when a beam is supported or leaned upon by more than two points. These states are considered static and undefined; they require some assistance from the theories of elastics and of the strength of materials. Such an analysis leads consequently to the formation and then to the need for a simultaneous solution of large systems of linear algebraic equations with many unknowns. It was well known in the 1930s how to solve these problems and the suitable equations were to be readily found in common textbooks. Nevertheless, even then, the solutions to these quite simple equations were bound within tedious manual calculations. Any doubling in the number of equations resulted in raising by the square in the number of variables and the increase to the third power of the number of calculating operations, meaning by eight times. By means of the slide-rule or the calculating machine, the upper limit of equations that could be solved was up to six equations with six unknowns. Beyond that, the number of calculating operations that needed to be executed was beyond practical feasibility. Moreover, the chances of error rose considerably during the setting of the data or the extraction of intermediate results on the slide-rule or the desk calculator.

The calculation of stress and loads of a complex ceiling, such as of a railway station of those days, demanded a system of at least thirty equations with thirty unknowns. The solution to such a system of equations required the labor of a team of several human calculators for several months. Yet this was precisely the type of problem for which static theory was supposed to provide results. Indeed, the textbooks and instruction books provided the required techniques for the solution of such problems. But, when reaching a solution required such extended durations of tedious calculations, what was good in theory turned out to be of no avail and vastly impractical.

This gap between the theoretical, as written in textbooks, and the real practical needs in the field spurred Zuse to tackle the problem by seeking some alternative. He noticed that while he was working with simple equations, he was following a mindless routine, doing more or less the same work in a fixed pattern, the variation expressed only in the setting of data into the equation itself. First he looked for new manual ways to solve these equations by means of paper forms being arranged in a particular calculating pattern. Later he considered the possibility of mechanizing these patterns.

Zuse's forms expressed a manual procedure for calculating. Zuse looked for and found a way to mechanize his patterned process for his paper forms. The turning point for the mechanization of that process came when he decided to represent the hand-written numerical data in the forms by the location of perforations. These perforations were by no means just binary notations like those used in any punch equipment. The data on the paper calculating forms were arranged in two basic patterns. In the first, the numbers were arranged on the same line, one next to the other, designed for multiplying or division operations. In the second, numbers were arranged in a colunm, one beneath the other, for adding or subtracting operations. By means of a sensor, reading and storage apparatus, like a crane able to move on two right-angle axes, the data ought to be retrieved from those punched forms *via* tiny pins like in Hollerith's punched card reader. Then the input would be transferred by means of an electric cable to an automatic calculating machine (to the standard of automation of the 1930s) to perform the required calculating operation. Then it occurred to Zuse that it would be better to utilize a mechanical accumulator, a type of storage to write and read data, which is by itself nothing but an imitation or analog of the form's pattern. Data would be fed into the accumulator and stored in it rather than on the perforated forms. Zuse reached an even deeper insight: there is no real meaning to the manner in which data are organized. Hence, he was ready to develop a multi-purpose storage device in which the addressing to it and from it would be accomplished by means of a numerical value [2]. To make the idea more explicit, imagine a two-dimensional matrix, enabling the placement in it of any data by means of indexing an address, represented by two values that indicate its exact place within the matrix. Such addresses are used in grid references on maps or in crossword puzzles, where the horizontal and vertical values of X and Y represent the location of an object or a word. In such a two-dimensional matrix it is easy to express values of indices for addressing, storing and retrieving data. Moreover, it enables no less expression of the proper instructions for a desired operation. What Zuse had achieved was the transformation of the paper form representing any two-dimensional matrix into a device in which this matrix had been imprinted into the hardware, the mechanical accumulator. The most fascinating part of this development is that Zuse had arrived so straightforwardly at the construction of a binary mechanical prototype of memory storage. For our purposes, a form of memory storage will be considered here as one featuring the addressing of an index as described here. He also concluded very quickly that it was feasible to integrate the actions of data-storage and of data-retrieval, based on the binary notation principle, with the data transfer operation to a mechanical adder that is an element for the performance of only addition operations, likewise based on the same binary principle. That is to say, he obtained a comprehensive system in which all components utilized binary notation. As we have seen, in order to serve as an index in hardware, a binary can be represented by typewritten letters A and B, or, alternatively, by numeric ones and zeros, or else by the X and Y coordinates within a graph.

I propose now a short digression into analog calculating devices, because they may help us to understand the later events in the USA and the UK, as well as the peculiarity of the devices presently under discussion. The major disadvantage of the analog devices, their accuracy and speed of calculation notwithstanding, is bound within the properties of the device in and of itself. This means that the analog device represents proportions, and can be applied to a certain type of problem of the same character, i.e., a single purpose device of a model that it is designed to imitate. But when our interest is in a diverse number of applications, the transformation from one application or model to another is in most cases quite unfeasible, while in the rest of the cases it is very complex. Thus, the transition requires the redesign and reconstruction of the system; each time then it is a different device. To put it more generally, every new task requires the alteration of the hardware. This was the principal drawback of the various analog calculating devices [3].

It can be said with a great deal of certainty that until 1943, for the solving of identical type of problems, the analog device was sometimes advantageously faster and more accurate than digital devices. And nevertheless, for counting and scientific calculations, particularly those in nuclear and quantum physics, the disadvantages of the analog device were likewise precisely its accuracy and speed [4]. Moreover, any doubling of the accuracy of an analog device required increasing the financial expenditure exponentially, whereas for a digital device it sufficed to increase the investment by only fifty percent to reach the same goal. In order to turn an analog device into a multi-purpose device, it was necessary to incorporate a program and control element, which is only partly feasible even within the serious limitations of an analog device. [5]

As Zuse expressed it in his patent application of April 1936, binary technology based on switches or relays of various types easily enables the construction of a digital automatic device [6].

The first model that Zuse designed was the Z1. It was an experimental pilot prototype, based on mechanical technology switches made of hand-cut metal strips and containing a logarithmic calculating unit, thus saving a great deal of storage volume. The device included an arithmetic unit ('unit', 'element' and 'component' are here used as synonyms) that contained a keyboard and a display board for input/output; a storage element; an instruction reader for the exposed punched photo film; and a punching device to perforate holes in the photo film. Despite the device being very slow and particularly unreliable, it nevertheless illustrated the feasibility of the idea [7]. Most of the components of this device were hand-made—by Zuse and his fellow students.

This is how Zuse passed from manual calculations to mechanized calculations in two intermediate steps. First he devised a pattern, an algorithm, for a strictly manual calculating plan in the paper forms with a specific pattern to ease the burden of manual calculations. Once he had grasped the principle of that pattern as a mechanical procedure, he decided to mechanize it. This was a crucial moment; the mere realization that one has a procedure does not necessarily lead to its mechanized representation. The primary handicap in the utilization of a mechanical procedure was the numerical data representation. How was it possible to make the translation of handwritten data, in a calculating form, into data that a mechanized means could read? Moreover, this passage, from handwritten data to punched data, is, to my mind, Zuse's turning point from manual to mechanized execution of calculations. This is a particularly exciting item, because the weavers of Lyon, France in the 18th century (Basile Bouchon and Jean-Baptiste Falcon) made an identical step forward in moving from designing silk fabric patterns on square grid paper to punched paper card or tape. That very paradigm passed down to Hollerith in the USA, the people of Bletchley Park in the UK and to the Polish mathematicians. This will be discussed further below.

Once Zuse had solved the problem of mechanically encoding the forms, what was left to develop was a sensor for reading the punched data. After all, punch readers and sorters were then common equipment. Nevertheless, Zuse skipped the execution of this stage, going directly to keyboard input/output. Moreover, when he had contemplated the development of an automatic photo-machine as a youngster, he had considered the possibility of applying the punch-card or some other sort of control based on punch hole codes [8]. He tried to develop such a handheld data-reader apparatus, based on a systematic scanning of the paper form by means of tiny pins, so that the numerical data would be transferred *via* an electric cable to an automatic calculator (like Hollerith's 1890 idea). Only then it occurred to him to give up perforated paper forms and use a mechanical accumulator instead. This meaningful technical leapfrogging is also ideologically important, since Zuse realized then that the mechanical reader by itself led him nowhere. Hence, instead of the reader and the perforated paper forms, he started to develop a sophisticated storage means, enabling the realization of numerical index addressing in order to store numerical data in practically considerable quantities [9]. Index addressing enables the storage of a numerical datum in any randomly-chosen register, for example the addressing of the number 10 to be stored either in location 2 or location 1000 in the memory cell's registers at will.

In 1936, Zuse devised a basic design of an automatic program-controlled digital calculating machine with a binary floating-point representation, a binary logarithmic notation that had an exponent and a mantissa. This device already had some sort of program control, fed from a 35mm punched photo-film. He arranged this program in a sequential series of instructions, yet it was not a programming language. Each instruction contained or indicated the execution of a particular action, written in a binary code, instructing the user how to manipulate the numerical data, through which register to address it and from where to retrieve it. Today this seems a machine code or machine language.

When Zuse asked a well-known machine manufacturer, Dr. Kurt Panneke, for financial aid in order to construct this machine, he was asked about its method of executing multiplication, if it was 'by iterate adding or an internal multiplying table?' Zuse replied that 'for my machine that is meaningless'. This answer was not accepted, at least not as self-evident [10].

By 1938, Zuse had completed the first prototype that he later named Z1 (initially V1, for *Versuch*—attempt—in allusion to its experimental character). It was unreliable. According to Zuse's account that he gave to me on 21st September 1986, it functioned only once in a demonstration and never again. At once he proceeded to the construction of Z2, in which the mechanical calculating element was replaced by electro-magnetic technology. Yet, the mechanical storage (memory) unit was preserved. Excluding the Z3 (1941), all other models that Zuse constructed during World War II had mechanical memory [11].

In 1938 Helmut Schreyer tried to design an electronic version of the Z1 [12].

The Z3 was the world's first practical automatic program-controlled digital calculating machine. It was a totally, completely electro-magnetic device; its construction was completed in 1941. It was financed and used by a German aircraft industry research organization, the *Deutsches Zentrum für Luft- und Raumfahrt e. V.* [13].

Schreyer proposed to the German authorities that they construct a fully electronic version of Zuse's concept of a calculating device that would have more than fifteen hundred radio tubes; his proposal was rejected. Instead, he started to construct a smaller pilot model of a calculating unit having just two hundred tubes; he stopped working on it in 1942 [14]. Of all of Zuse's war developments, only the Z4 survived. Zuse's work during the war appeared for the first time in the periodical *Mathematical Tables and Other Aids to Computation (MTAC)* of 1947 [15], while the first mention of the Z3 was in 1966, in the semiprofessional publication *Datamation* [16].

Zuse established his own firm in 1943 to manufacture two single purpose devices meant to test the strength of aircraft wings [17]. After the war, in the early 1950s, he reestablished his firm and work on computers. In the late 1960s, his firm was taken over by Siemens.

I will briefly sum up the events leading Zuse to the development of an automatic program-controlled digital calculating machine. He looked for a way to eliminate repeated static calculations in the solution of large systems of linear algebraic equations that had many unknowns. He tried to achieve this by the then common matrix technique. First he determined his own algorithm for these static calculations. Then he extended and improved this algorithm for additional calculations by utilizing the plain paper calculating forms. Finally, he passed from these forms to a pattern of perforated paper forms. The data from these perforated forms was meant to be collected by a sensor and transferred electrically into an automatic calculator, where it would be automatically deduced. The principle of binary notation was integrated at once by moving from handwritten data to punched data. This was a passage from a totally manual process to a semi-mechanized one, of punching numerical data and their reading, collection, storage and electric transfer. Only then did the idea occur to him to move from a single register (accumulator) of data, serving as a sensor, reader and transferor of data, towards the development of an array of many such registers serving as a multi-data storage device, making them into a memory. This unique solution of Zuse's further provided direct index addressing, enabling the flexibility of directly or indirectly diverting data from and to any of the memory registers. This way, data set-up in any particular location in the memory could be manipulated at will with and by any other data.

At his technical higher education school, Zuse was confused as to the selection of his profession. He started with machine engineering and finished as a construction engineer. To the question, why he turned to develop a computer, he replies in his biography: 'Because I got fed up with repeating the static calculations' [18].

How then did Zuse's education, work, deeds influence his formalization of a part of mathematics and the devices that he developed to house it? I reckon that we can now rephrase this question by adding to it an explicit reference to a hidden assumption—that Zuse's education, work, deeds have somehow influenced his formalization of a part of mathematics and his development of devices to house it. As stated at the beginning of this chapter, the issue of such links is complex and it is hard to determine what has caused what and how. I found nothing unique or outstanding in Zuse's education that could lead him to the development of such devices, nothing that has not also been found in the education of Schreyer or other members of his peer group of students at the same school or elsewhere. His formal education as a construction engineer and his work in static calculations in an aircraft firm or his being involved in acting or painting are neither sufficient nor necessary conditions to turn anyone into an inventor, let alone an inventor of a calculating device. When Zuse started his development of calculating devices he had no idea at all of Hilbert's work, or of the formalization of mathematics. Moreover, only after he had come up with the idea and designed and developed his device, in 1943, did he turn to mathematical logic and wrote an article very close to ideas that Shannon put forth in his 1938 paper.

Evidently, the construction of an algorithm and the application of a program may dictate the use of a code and the development of some sort of formal language, precisely as Zuse did. But the question still remains as to what extent these concepts and notions of mathematical logic may have been integrated into such work. The answer is hard to tell. Perhaps Zuse had been influenced (a term that I dislike) by the introduction of vending machines and by the transportation problems that had bothered him as a teenager. It is true that even this link between the cigarette vending machines and the automatic photo-machine or the link between the transportation algorithm or flowchart and the development of the automatic program-controlled digital calculating machines is easy to refute, as was exhibited in the summary of Part I. (Even the idea of a flowchart, first explicitly presented in 1921, is absent from the early discussions of the development of the computer; in retrospect, it is obvious that it contributed significantly to the idea of programming.) Zuse's example provides sufficient evidence that he acted independently and in ignorance of any, previous or contemporary external influence of mathematical logic, as well as of his colleagues working on these devices in Germany or elsewhere [19]. There are many examples in which it is easy to determine precisely when and who arrived at a meaningful breakthrough—even when these were not conspicuous professionals. Due to their 'professional ignorance', they explored untouched corners and took paths that the professionals had neglected and ignored. The professionals, being captives of their own prejudices and unable to free themselves from the unseen mental shackles, were unable to do what Zuse, as a youngster of 24, saw as obvious. Eckert also exemplifies this phenomenon. All the experts rejected then on the spot the idea of constructing a device having several thousand tubes. And, at the age of 24, Eckert proved by constructing it that it was possible.

What characterizes uniquely the inventors and developers? This question, interesting in its own right as it is, exceeds the scope of the present work. I will consequently end the exposition on Zuse here with the argument that it is impossible to determine from Zuse's example as to what caused him or led him to the development of automatic program-controlled digital calculating machines. I must lean towards concluding that the traditional claims in the literature as to the causes of the introduction of these devices are not sufficiently grounded in today's historical knowledge. This begs the question: what is the contribution of the present work? My answer is that my contribution here is in narrowing the field of remaining viable hypotheses by refuting the standard answers given in the research up until now, thus reopening the debate. For such is Socratic enlightenment by refutation. Therefore, here is the answer to the question raised in this chapter: how did Zuse's education, work and deeds influenced his formalization of a chunk of mathematics and his introduction of the digital computer? It is as follows: it is unfeasible to provide such an analytical result, because it is impossible to determine something unique in Zuse as compared to thousands of other students who were also then in Charlottenburg, Berlin, elsewhere in Germany, or in other locations [20].

The United Kingdom: From paper to electronic storage

The events in the UK differed sharply from those in Germany. In 1939, the outbreak of the War heightened the demand for deciphering intercepted wireless communication codes. The process of deciphering until the War was in essence manual. The use of mechanized encoding had been known for years. As a result of the capitulation of Poland, the Polish secret service delivered to the UK most of its developed deciphering methods that had been in use since 1938, for German mixing, encoding and decoding of the electro-mechanical machine called the 'Enigma'. The Polish deciphered the Enigma's intercepted messages at the outset by means of square printed sheets of punched paper. Later they succeeded in constructing an electro-magnetic decoding device that they named 'Bomba'. The Enigma (meaning a puzzling or inexplicable occurrence or situation or a riddle, likely from the Greek *'ainigma'* or Latin *'aenigma'*, meaning 'obscure') operated on the principle of encoding-mechanism with cogwheel-gears driven by electric motors. The early Enigmas each had a set of three such wheels as was the standard in the German Army, while in the German Navy the number of wheels increased subsequently to four. The wheels could be easily removed and re-arranged in a desired order, thus three wheels could provide up to six different arrangements of combinations. On the external circumference of the wheels was a ring imprinted at random with twenty-six letters of the ABC alphabet, coinciding with the number of twenty-six teeth (as against the ten teeth in the decimal calculating-counting wheel). The wheels were arranged according to a defined key, and the starting point of the letters on each wheel was set. Then the machine executed automatic encoding by directly translating the keyboard input of free language text letters into an output of a complex code of electrical pulses. The Polish succeeded in copying the German Enigma and connected the Bomba to it, which created an analog of the Enigma in order to decode, or more precisely, break the cipher of the wheels’ combination and the order of the alphabetic letters. The Enigma used at the outset of the war had only three wheels enabling six combinations; what was left was to deduce the arrangement of the initial letter on each of the wheels and the electrical pulses’ circuit connections between the wheels [21]. However, at the beginning of 1941, the Germans introduced a fourth wheel to the Enigma, making the matter more complex. It is interesting to note that the British decoders tried to solve the problem in a very similar manner to Zuse. First they utilized the Polish square paper sheets, on which were all the possible combinations of the four wheels of the Enigma that it was possible to encode. The (fixed) letter setting of each wheel was on a separate square paper sheet. They obtained four one-dimension matrices. The square paper sheets were perforated with suitable code holes to represent the various letters of the alphabet. Then the perforated sheets were set up one upon the other until the desired combination of the key code were reached. It was sufficient then to use a certain part of the encoded intercepted text to perforate holes for it and then compare it to the settings of the perforated square paper sheets until the key code was found. The procedure resembles the sieve stencils process (see Chapter 2). However, there were two approaches to breaking the key code of the Enigma. One was proposed by R. V. Jones, a physicist from Oxford, then chief scientist of British intelligence; it was the use of the statistical occurrence of an abundance of the various letters in the text. It is well known that in a given language certain letters appear more frequently than others. Certain combinations of letters are also more abundant than others. This use of the statistics of syntax of the words of a language is a very useful means for breaking codes. A detailed study of the statistics and abundance of letters and their combinations in the German language can be found in W. Jensen (1952) [22]. This property of the abundance of the letters in a language had been applied already by Vail, Morse’s partner in the design of the Morse code. The method proposed by Jones is ineffective for decoding short messages, however, because the sample group of letters is too small [23]. The alternative method was to search for frequently repeated words in the communication traffic and to break the code through them. This method was adopted by the team at Bletchley Park [24]. Using this technique, the breaking of the code was achieved by the help of the matrices-maps of the deployed wheel letters and scanning after the proper combination of a certain word, the location of which in the telegram was known in advance due to the German routine in sending messages. It took a short while until the Bletchley Park team realized (at the beginning of 1940) that this manual mechanical (in the sense of mental process) procedure could be mechanized and completely automated. ‘What is encoded by a machine can also be decoded by a machine’. They (Turing) also found statistical ways to eliminate various irrelevant combinations from the process, thus cutting the time of decoding [25]. This is the most important factor in deciphering information in real time.

In May 1941, the first British ‘Bomb’ was activated. It was an electro-magnetic device, designed for decoding Enigma messages. Its principle of operation was a practical imitation of the manual process. The square perforated paper matrix sheets were replaced by perforated paper tapes, likewise applying a code in binary notation. The binary code and the perforated paper tapes were nothing strange for the Bletchley Park team, as they had used teleprinters and tabulating punch-card equipment even before the outbreak of the War. The Bomb performed an automatic process of sorting out all available combinations of the letters of the enigma wheels, represented in closed loops of punched paper tapes. In addition, a separate loop of punched paper-tape was installed, containing the text of the coded message. When the machine reached a parallel to its coded term it stopped. This process could last up to six hours, as against the manual process that could take several days. The British Bomb, though it had a similar name to the Polish Bomba, identical in meaning, differed from it. It rested on a logic sorting principle and was totally electro-magnetic, unlike the Polish one that applied mathematical calculating principles.

It is known that Turing participated in the team that designed the Bomb at Bletchley Park [26]. It is doubtful that direct or indirect link between his 1936 paper ‘On Computable Numbers’ and the design of the Bomb. The idea of Turing’s universal machine, however, strange as it may seem, could have derived from the typewriter or the teleprinter: the setting of the typewriter made it print a single character at each step and then move one step further, utilizing an endless carbon ribbon, like the tape in the Turing machine. Apparently, Bletchley Park executed an inverse process to that explained in Turing’s paper on the universal machine, the transformation from strings of meaningless symbols and their translation to a meaningful output by a typewriter. The design of Bletchley Park’s Bomb was a product of the work of a team including Turing and Cambridge mathematician William Gordon Welchman (1906-1985), then in charge of the design of the Bomb at Bletchley Park [27], while development and construction was carried out by the British daughter company of IBM, British Tabulating

Machinery. Of the various Bomb models (named for the awful racket made during their operation), dozens of units were constructed. In America a similar device was also developed by Vannevar Bush at MIT and NCR (possibly by Stibitz and Bell). Nevertheless, in 1943, negotiations between the USA and the UK took place on American purchase of some hundred British Bombs [28].

In February 1942, the German ciphers turned out to be much more complicated to decode, due to new methods of applying binary codes to the teleprinter. The Bletchley Park team had a decision to make at a crucial junction, either to increase the number of Bombs or to choose a new course of action [29]. At first it was considered that in order to maintain the previous rate of decoding, sixty-four additional Bombs would be needed to decode each of the messages in the new code. Later, by the statistical elimination of certain states, they came to the conclusion that twenty-four would suffice for each additional task. Among the other alternatives raised was the improvement or upgrading of the existing Bomb or the construction of an electronic device. To examine these alternatives, the best available people in these domains in the UK were mobilized (such as Wynn-Williams and government organizations and establishments who worked with electromagnetic switching and electronics, such as the Post Office and TRE) [30].

Between February 1942 and December 1943, the UK faced the most significant difficulties in breaking the German codes, though the British were lucky and from time to time succeeded physically in getting hold of German key code books. in that period, Turing turned to binary digital voice encoding. The need for a trans-Atlantic voice-operated communications system for coordination between Roosevelt and Churchill grew once it was decided on the landing on the continent of Europe. This is the historical context of Turing's visit to the USA between November 13, 1942 and March 31, 1943. On this issue he worked with Shannon at Bell Laboratories and with others [31]. He saw Bell's MODEL III, but was unimpressed [32].

Meanwhile, the Bletchley Park team asked for the assistance of Wynn-Williams in their efforts to develop and construct electronic versions of the Bomb, utilizing photo-electric readers. The first of these was activated in April 1943 with a considerable number of malfunctions. It was decided then to proceed with the construction of a new electronic device, different from the Bomb. T. H. Flowers, a professional and highly experienced telephone engineer, was appointed to head the team. This project received top priority from the state, and within nine months it was completed; it was operational in December 1943, and was named 'Colossus' [33]. It was constructed under the strictest security measures, so that only three people, T. H. Flower, S. W. Bradhurst and W. W. Chandler, shared every one of its secrets. The various components were constructed in the British Post Office plant in Birmingham, where no one had the slightest notion as to the purpose of their labor. In the first version of the Colossus, some fifteen hundred radio valves were combined in its logic circuits. It was fully automatic and once the data were set, it needed no human intervention during the whole decoding process. It was two thousand times faster than the Bomb and was capable of working on several encoded texts concurrently. It also comprised an automatic printed output, accomplished by means of an IBM electric typewriter brought specially from the USA. Unlike the Bomb and other past decoding means, the Colossus was unique in its imprinting of the enigma's alphabetic wheel patterns not on punched paper tapes but into the hardware itself, namely into electronic logic circuits, thus reducing the preparations for its operation to nil and eliminating malfunctions caused by the punched paper tapes, resulting in an enormous increase in the speed of its operation. Until the War ended, 12 to 14 Colossus engines of various versions came into operation [34].

Despite the Colossus being in essence a logic-based device, it was obvious to its operators that it was capable of performing other applications as well. Turing assisted with its design mainly on a statistical level, by reducing the number of possibilities in decoding, and not so much on technical aspects [35]. It bears mention that, at Princeton in 1937, Turing constructed a binary electro-magnetic multiplier, based on the translation of electrical logic circuits from 'AND' and 'OR' logic (though back then it was not yet so termed) [36].

In conclusion, the events in the UK linked with the appearance of the automatic program-controlled digital calculating machines proceeded at Bletchley Park in two phases, both being imitations of a manual mechanical (mental) sorting procedure of decoding. The first phase in this process was accomplished by an electro-magnetic device, the Bomb. Later, the need for a much faster means of decoding brought to bear the development of an electronic means, the Colossus. This is an exceptional case in the development of the automatic program-controlled digital calculating machines, as it was only in this case where the factor of speed—intelligence information in real time—was crucial for its development. The need for a higher speed of operation resulted in the shift from electro-magnetic technology to the new technology of electronics in an unprecedented period of nine months [37].

World War II drastically accelerated this development. Indeed, it was its main cause. So here we may explicitly claim that the Colossus was a result of the war effort. In addition to the factor of speed, what makes the British devices unique is the logic aspect, as against the devices developed in the USA or in Germany. To my regret, all evidence provided here rests on secondary sources of partial information and personal recollections that have been published by people involved in the project. I obtained some notions on it from Professor Joseph Gillis (1911-1993) at the Weizmann Institute of Science, Rechovot, Israel, who was back then at Bletchley Park. Nevertheless, the concealed exceeded the revealed in a discussion held with Professor B. Randell on this issue (on 14th March 1987 at his home). I realized that when he talked with the people involved in the development of the Colossus, they had difficulties in recollecting details as to its development and as to who proposed what, etc.

Returning to the matter at hand, even if we are not familiar with all the technical details and with who proposed what, we may conclude the following.

A. We are dealing here with automatic program-controlled digital calculating machines that are much more advanced and sophisticated than anything known before, and even anything else until the 1950s.
B. With regard to the evidence as to the British approach and active process, they knew how to mobilize their best brains and set proper priorities, concentrating their national resources towards the war effort. This does not mean that Turing and his colleagues were pleased with the speed of events. On one occasion they did not hesitate to write to Churchill, who had seen them as 'geese that laid the golden eggs and never cackled', and complain that things did not move with proper dispatch [38].

A part of the official documents linked with the means of decoding were recently declassified. The added information that this offers may influence the historiography of the computer and even that of the whole history of the management of the Second World War. Yet first there is a need to clear the slate of myths that have meanwhile accumulated.

One last point, related to the cooperation between the USA and the UK in decoding in general and that of automatic program-controlled digital calculating machines in particular, is the existing evidence of such cooperation and, apparently, also of the exchange of Bombs between these nations [39]. It is obvious from the evidence that the information obtained *via* these devices was exchanged as well, including that of the Colossus [40]. Yet I doubt that the British disclosed the secrets of the Colossus' design itself to the Americans, even though American liaison officers were present at Bletchley Park.

On the other hand, in the USA, Turing and other visitors were allowed to see the American calculating devices, though I have no indication that they had access to the American decoding. Turing was not impressed by the American developments, and this was a mutual appreciation of Turing's developments at NPL. Goldstine, who was the Army representative on the ENIAC project, in a discussion with me on Turing's report on the ACE, written in 1945, said of it, 'that it is too complicated' [41]. It seems that Goldstine, then, did not grasp the difference between Turing's and von Neumann's approaches. While von Neumann deemed the computer a calculating device, which is a limited notion, Turing deemed it a universal machine, aimed at imitating the functionality of the human brain itself—what came to be known as artificial intelligence. Turing was of the opinion that the right way to go about is to limit the hardware to a bare minimum and to compensate this by means of expanding the software. This puts a special emphasis and focus on the software. Von Neumann, who was a captive of realistic applications, stressed the comparative practical advantages that the use of hardware had. Hence, the controversy. Turing and von Neumann placed themselves on different levels. Pragmatists of the sort of von Neumann and Goldstine in the USA and in the UK turned towards the easing of the burden of programming by the addition of hardware components, in oversight of what captivated a mathematical logician like Turing. Turing desired to design a device in which the use of hardware was a bare necessity and the main burden of the logical calculating would be done by the programmer and the program. This is quite an interesting topic, but exceeds the scope of the present work.

The United States: 'And they asked for many calculations' (*Ecclesiastes*, 7:29)

In the USA the events connected with the development of automatic program-controlled digital calculating machines occurred in parallel in four different and separate locations: Iowa College in 1937 by Vincent Atanasoff; Harvard University in 1937 by H. Aiken; Bell Laboratories in 1938 by George Stibitz; and Moore School for Electrical Engineering, the University of Pennsylvania in 1942 by John Mauchly and John Adam Presper Eckert.

Atanasoff: From an elimination process for linear algebraic equations to a binary digital electronic device with rechargeable memory

At Iowa College, already by the 1920s, some experimental work was underway to apply commercial IBM equipment for statistical calculations. Atanasoff and a student of his, Lynn Hannum, constructed in 1935 an analog device, the 'Laplaciometer', to solve Laplace equations in two dimensions. Atanasoff was then involved with the analysis of problems of complex spectra which required the solution of large systems of linear algebraic equations, typically in applied fields of statistics, physics, other sciences and technologies. Already in 1933, he investigated the feasibility of a mechanized solution for these problems. An examination of the theory of such systems of equations reveals one of the more practical methods, the well-known process of successively eliminating one variable between pairs of equations until an answer is obtained. After Atanasoff had formulated the general outline of a plan of mechanizing this elimination process, an attempt was made to realize it by using the computational capacity of the IBM punch card tabulating equipment. It was soon abandoned, principally since extant computational capacity was simply inadequate for the task. At a certain point, Atanasoff decided to move to decimal digital calculating techniques.

The first practical effort in the USA to construct a totally electronic calculating device was, probably, by Atanasoff. Since he had previous experience in electronics and had some idea of Eccles and Jordan's achievement, he at once grasped the tremendous advantage of utilizing electronics for calculations. Moreover, he also conceived the great advantage of applying binary notation. In approximately 1936-1937, he abandoned the idea of the Eccles-Jordan trigger as a component for latching onto information and as the principle logic and calculating circuit. In about 1938 he designed his own logic circuit. He was interested in developing a device capable of solving up to thirty linear equations simultaneously. A memorandum of his from August 1940 provides an account of the operation of his device, and the ideas and reasons that led him to choose binary notation [42]. The device was activated for the first time in May 1940 to the satisfaction of the developers, except for the photo-electrical binary card reader that was not yet sufficiently reliable. In August 1942 the project was abandoned. As many consider Atanasoff a 'pioneer' of the electronic computer, I will indicate parenthetically that Norbert Wiener claimed that he had given Vannevar Bush a report that included a recommendation for the development of a binary electronic program-controlled calculating machine. That document is in the MIT archive [43]. Moreover, also at MIT, during the period 1938-1942, a project was underway to design and develop an electronic digital calculating device known as the ‘Rapid Arithmetical Machine’, sponsored and financed by MIT and NCR. This project rested on a 1936 paper of Bush, ‘Instrumental Analysis’ [44].

In his memorandum of August 1940, Atanasoff showed that binary notation simplifies and eases the technical construction and that the binary notation increases storage area by 3.34 [45].

The most important controversy over the device that Atanasoff and his assistant Berry developed, the ABC computer, turns upon on the issue of its multi-purpose functionality. Even though the ABC was abandoned and lost, nevertheless, clearly, Atanasoff's memorandum (1940) and Berry (1963), described it as a single purpose dedicated device: ‘The machine was designated for a single purpose, namely to solve large sets of linear simultaneous algebraic equations (up to 30x30).’ [46]. Berry continues, claiming that Atanasoff was aware of other people’s work in this field, Aiken for example, saying,

> ‘I am sure that he was aware of the early work in the field, and I recall we were at least aware of Aiken’s ‘relay’ computer although we may not have known much about it.’ [47].

Therefore, I doubt whether the developers of the ABC were aware of its multi-purpose functionality, let alone the general purpose or even universal functionality of their device. My reservations are further detailed in Appendix B, ‘The Borrowed Fame’.

What is important is the evolution of Atanasoff’s thinking between 1935 and 1938, on the adaptation and mechanization of a hitherto manual process of elimination, and its implementation in hardware. First Atanasoff improved the slide-rule, then the desk calculator (Monroe), and later the construction of an analog device, the shift towards the punch and tabulating equipment, and networking the devices under a control as a modified telephone exchange design [48]. Finally, he then turned to digital binary notation, iterate calculating techniques, and the adoption of electronic technology.

Stibitz: from optimal properties of a telephone relay to a relay telephone 'computer'

In around 1936, at Bell Laboratories, George Stibitz worked on the improvement of an electro-magnetic relay that this telephone company used. He then investigated the properties of that relay *via* mathematical analysis in search of the best method to represent such a relay.

In 1937 he independently began experiments with electro-magnetic relays. First he devised binary adding circuits for which he then developed configurations for multiplying and dividing circuits based on bi-quinary notation (a combination of base two and base five notations). He also incorporated a conversion system from decimal to binary and *vice versa*. He also applied binary decimal notation a combination of base two and base ten notations).

During one of the weekends of October-November 1937, Stibitz connected two relays on a board, to use as an input mechanism. He also purchased a few batteries and flashlights, to use as the output mechanism, attaching to it the binary adder. With this device he could add two binary numbers of two digits each. When he made an input of a digit having the value 1 the flashlights illuminated, and having the value 0 not light it up. He showed this adder to his colleagues at work; no one was impressed.

The next task he set for himself was to find a way to treat a number with larger than two binary digits. He came up with the idea of decimal binary notation. The problem he faced now, however, was how to transfer a carry, because it required a more complex logic circuit. He turned to the bi-quinary notation, as he found it more economical. Close to this event, Stibitz proposed Dr. Fry, who was in charge of the mathematical department at Bell Laboratories, to use his binary adder for calculating complex numbers [49]. In November 1938, a project team at Bell was assembled to develop a calculating device for complex numbers. Heading the project was Sam Williams, a switching engineer by training, but who, to quote Stibitz, was 'lacking mathematical knowledge and the number theory'. The device was constructed between April and October 1939 and completed at the end of 1939. Stibitz says that, even by 1938, we 'knew' on paper how a computer ought to operate in principle, but putting it into practice was more difficult. It was a thrilling intellectual adventure. The components required for binary calculation differed so much from common gears revolving in the conventional hand calculating machines of the day that many refused to believe that relays were capable of complex tasks at the high required speeds. The operating speed of a telephone relay is limited to a tenth of a thousandth (one hundredth) of a second. [50]

After some tests and checks the device became operational in January 1940. It was the Bell MODEL I and named the 'Complex Computer'. Its purpose was to carry out the addition and subtraction of complex numbers. Terminals with teleprinters were connected to the device for input and control. This device was displayed in operation by remote control in September 1940 at the American Mathematical Society annual meeting at Hanover NH—from its location at Bell Laboratories through a teleprinter terminal and telephone lines at a distance of a thousand kilometers. The complex computer did not yet incorporate a sequential control unit, and Stibitz worked on it between 1939 and 1941 [51]. He also developed a special code to prevent errors. Thus, Bell devices of this type were characterized by accuracy and reliability, though they were relatively slow in execution of calculations. Later, Stibitz's involvement in the development of automatic program-controlled digital calculating machines was expressed mainly in consultations. Bell lent him to the National Defense Research Committee (NDRC).

Bell's MODEL II, the 'Relay Interpolator', was devised for fire control. It was constructed under an order made by the NDRC, and it went into action in September 1943 [52]. It included a simple control mechanism for fire control data simulation, fed from a punched paper tape. The Bell MODEL III, the 'Ballistic Computer', work on which started at the beginning of 1942 and was completed by June 1944, incorporated a better control-mechanism than the Model II, with punched paper tape input augmented with a small memory [53].

Stibitz's involvement in the development of Models II and III at Bell was extremely limited. During the period 1944-1947 several additional models were constructed at Bell: Models IV, V, and VI (each in several copies), as well as improvements upon the Bell model III, are irrelevant to our case. But Model V, constructed in 1945, is of some importance, as it was initially planned as a general-purpose device.

To conclude the events at Bell pertinent to the development of automatic program-controlled digital calculating machines, Stibitz's of the binary adder development—'by chance or at random'—that had properties similar to Turing's multiplier, deserves attention. The adder, termed by Stibitz as the 'K' computer (for Kitchen Computer), comprises a feasibility test of an idea or a task: to perform calculations by means of telephone relays. Stibitz' adoption of the binary notation does not necessarily derive from the technology utilized that was the electro-magnetic relay. Perhaps the adoption of the binary notation resulted from the frequent use of drawings in which the presentation is explicit of the binary property of the switches designated as relays.

The Bell devices excelled in their accuracy and outstanding reliability. For example, the Model I worked non-stop from 1939 to 1949. To obtain high standards of precision, very stringent tests were introduced. What makes the Bell 'computers' unique, like the devices of Bletchley Park, is that they were designed as simulators to represent particular and practical problems, such as the solution of complex number additions, simulation and testing of fire control systems, and practice for anti-aircraft gunners.

As a member of the NDRC, Stibitz represented a concept, perhaps even an economic interest, that supported and prioritized the development of electro-magnetic devices. This concept rested on the claim that in the construction of such devices, electro-magnetic components were more reliable, cheaper and faster than those constructed with electronic components. Experience in these components was then only beginning. This presents a confrontation between two doctrines and aims, one that had grave consequences on the development of automatic program-controlled digital calculating machines between 1943 and 1950. The dispute between the supporters of the electro-magnetic components—Aiken and Stibitz—and the supporters of the electronic components—Mauchly, Eckert and von Neumann—was resolved in 1949 [54].

Aiken: from an iterate process for polynomials and differential equations to an automatic calculating device

At Harvard University, as Aiken was working on his PhD dissertation (1935-1936) in physics, he faced difficulties with differential equations that he could not solve by analog devices [55]. The solution of those equations required laborious large-scale calculations. Being a graduate of electrical engineering, and having worked for a long time as a telephone exchange operator, he was able to construct two electro-magnetic calculating devices. (See his biography above.) The first model was designed to solve simple polynomial equations. The other was meant to solve much more complex polynomial equations. To his surprise, he found that there was no essential difference between the two models in their functioning procedures [56].

In a memorandum of 1936, Aiken presented the problem and argued for the need of an automatic calculating device for scientific calculations [57]. In his opinion, the accuracy of the then existing calculating equipment was insufficient, as it caused delays in the development of mathematics, physics and other sciences. He described the difference between the equipment needed for commercial and for scientific calculations. It is probably one of the first such distinctions on this issue. He claimed that an automatic calculating device based on standard equipment found on the market, such as that of IBM, could easily be constructed by combining it with an electric connecting board similar to a telephone manual exchange. IBM responded to the challenge and entered into the project together with Harvard University, allocating three distinguished engineers to work with Aiken. The construction of the device started in 1939 at the IBM laboratory at Endicott, New Jersey. It was named the Automatic Sequence Controlled Calculator (ASCC)—Harvard Mark I for short. After its experimental run in January 1943, it was moved to Harvard, and operated anew in May 1944. At the official inauguration ceremony on 7th August 1944 it was donated by IBM to Harvard. It was an extremely large device, being mainly mechanical and incorporating electro-magnetic systems. The calculating technique was in decimal notation, so that the electro-magnetic switches imitated the stepped reckoner wheel as the calculating element. The machine operated at Harvard until 1959. Parts of it are exhibited in the Aiken Computing Laboratory building at Harvard University.

For a long time, historians of the computer considered Mark I the first automatic program-controlled digital calculating machine [58]. This is an error, since the devices of Zuse, Atanasoff and Stibitz clearly preceded that of Aiken. As Aiken was a member of the NDRC together with Stibitz, he was greatly influential in the development of the automatic program-controlled digital calculating machines during the period 1944-1950. In the development of automatic program-controlled digital calculating machines, Stibitz and Aiken recommended the use of electro-magnetic technology rather than the use of electronic devices [59].

After the construction of Mark I, Aiken and IBM parted ways [60]. He constructed two additional electro-magnetic models; the inauguration of Mark II, work on which began in 1945, was the cause for the first Harvard symposium on large-scale calculating machinery, held in January 7-10, 1947. ('Large-scale' indicated the property of the large amounts of calculations that the machine was capable of performing, not its bulk.) The work on Mark III started in 1947 and its inauguration served as the pretext for the second Harvard symposium that took place in September 1949.

The various Harvard symposia and the establishment of Harvard's Computing Laboratory, of which Aiken was a director until 1962, made Harvard the leading center for the training and graduation of computer science students for many years [61].

After the break between Aiken and IBM (the reasons for which are of no interest here), IBM also developed an electro-magnetic calculating device, called 'Pluggable Sequence Relay Calculator'. Its developing team included two of the designers of Mark I: B. M. Durfee and C. D. Lake. This device was still in the tradition of IBM's punched calculating equipment, of which several samples were delivered in December 1944 to the US Army and to the Columbia University Calculating Laboratory. Its control, as its name indicates, rested on an electric connecting plug-board with a sequential control of undetermined length: it could be changed by means of punched paper tape, similar to that of Mark I. Already in 1934, IBM had constructed a calculating device for the Columbia University Calculating Laboratory, incorporating the IBM-601 multiplier with other punch tabulating equipment by means of a connecting plug-board, enabling the determination of what action was to be performed on defined fields of the punched card. Thus, the length of the sequence of operations that it could perform was limited. This very feature, among others, renders the device specific rather than a general purpose device.

In 1945 IBM undertook a secret project to construct its first electronic digital calculating device named for its characteristics and method of operation: the 'Selective Sequence Electronic Calculator'. It was a gigantic machine, nicknamed 'the monster' for its sheer enormity. It went into action by January 1948; it was dismantled in 1952 [62]. It exhibited a compromise by the designers to obtain a balance between electronic and electro-magnetic components. These designers were the astronomer Wallace Eckert of the Columbia University Calculating Laboratory, who advocated the application of electronic parts, and F. Hamilton, the chief engineer who had previously worked with Aiken on Mark I, who preferred the electro-magnetic relays due to their reliability. It is possible that 'the monster' was the first automatic program-controlled digital calculating machine to incorporate internal storage of instructions.

Aiken's development reflects, then, a disposition that prevailed since the end of the 19th century, to integrate punch card equipment into a comprehensive system by means of an electric connecting plug-board. Its commercial applications took place in the USA, Austria and other places. In Germany, for instance, at the beginning of 1944, an automatic program-controlled calculating device was constructed from IBM equipment, akin to that of Aiken. its development had been abandoned due to a lack of spare parts. It was destroyed during the air raids of September 1944. [63]

Most commendably, Aiken saw to it that the Mark I Patent would recognize as its co-inventors the three IBM engineers, Hamilton, Lake and Durfee.

Other than in its control system, Mark I made no particular change to the standard IBM equipment. The device functioned on decimal notation and its calculating element possessed an electro-magnet that imitated the cog-toothed wheel.

To the questions of why did Aiken do what he did, and what brought him to the development of his device, the common answer is that it was the need for a suitable calculating device to solve polynomial equations, as he could not solve or analyze them by existing tools. As to the technical solution that Aiken has provided, this matter is under controversy. Perhaps, in the first place he tried to provide a solution by means of a mechanical device, specifically by utilizing a Monroe mechanical desk calculating machine integrated with a control mechanism of an electrical connecting plug-board. It is also possible that the cause of the Monroe firm's rejection of Aiken's proposal was a reluctance to embark on an electro-magnetic technology. However, to repeat, there is a claim that Aiken had already constructed (1935-1936) two electro-magnetic calculating devices. In any case, the decisive turn of Aiken that resulted in Mark I, is found in the application of the punched paper tape control to provide the device with multi-purpose functionality, the use of the difference method in solving the polynomial equations and in the installation of checking means against technical errors made by the machine or by the human operator. Still, there is no sufficient explanation in the 1937 memorandum, or anywhere else, of Aiken's having turned to electro-magnetic technology. It is a complicated task to determine the relation between Aiken's work and deeds, the formalization of mathematics and the design and development of his automatic program-controlled digital calculating machine. It seems apparent that there is at least some link between his work as a telephone exchange operator and the use of the plug connecting board in the integration of the various discrete subscribers and the various units of IBM equipment into a single communication system. I have not found any specific link between the formalization of mathematics or mathematical logic and Aiken's developments. As a chief electric power engineer in a gas company during the period 1923-1935, Aiken, a practical mathematician, gives no indication that he was troubled with or aware of problems that occupied the minds of mathematical logicians. The problems he tried to solve belonged to the practical *milieu*. With the design of his device, he tried to overcome and reduce errors as much as possible, by the approximation method typically applied for the prediction of physical processes; the bottom line for Aiken was the calculation of numbers in order to arrive at a final result.

I am of the opinion that what Aiken wanted to achieve was a device that could deduce mathematical tables and values of polynomial functions beyond the reach of the then available technology in order to get more accurate results during experiments, etc. In support of my claim is the following case in point: the very first applications of Mark I, as their principal use, was the deduction of mathematical functions tables, following the trend taken by Müller, Babbage, Eckert and Comrie. Mark I was also used for the deduction of artillery ballistic firing range tables. Von Neumann got permission to use it once a week from the middle of 1944 for calculations bound to the Manhattan Project in Los Alamos. Mark I was also utilized for calculations in ship engineering for the US Navy. For its extended use to calculate a Bessel function, Mark I earned the nickname 'Bessie'. The challenge of computing Bessel functions was probably a motivation for Aiken to construct this device in the first place. Such functions describe physical phenomena in terms of the rate of change of the ratio of quantity in relation to time; they are differential equations that represent change. Equations of the second derivative and above create some time complex values of the independent variables, and hence also the various types of Bessel function integrals. The use of Bessel functions is common in science and engineering. An example of such an application then was in the resonance of various bodies in communication and wireless broadcasting. The first occasion where such a function was calculated by Mark I was in August 1944. It was the duty of the engineer to determine (by numerical analysis, which then did not yet exist as a discipline and did not bear this name) which of these, if any at all, was applicable to the desired problem. This was usually the complex part in the analysis of a physical problem. There then remained the need to analyze and assess the Bessel function itself. In their periodicity and orderly behavior, Bessel functions resemble trigonometric functions while passing through the zero of one of their axes (termed the zero of the Bessel function). there is no shortcut to carrying out such an analysis, as in the case of trigonometric functions. Here, since the 19th century the use of polynomial approximation analysis techniques for solving these equations was common.

The task designated for Mark I was then the production (calculation and printing) of tapes of the Bessel functions, by the use of suitable polynomial approximation techniques for a wide range of constants. The work carried out by Mark I was so reliable and comprehensive that it remained in use for years, long after Mark I was officially decommissioned (1959).

Given all this, there remains a difficulty in finding any sort of link between Aiken's education and work experience, both as a civilian and as a naval officer, and the formalization of mathematics and the appearance of Mark I. At best, it remains controversial.

Mauchly: from meteorological forecast to high speed calculating with vacuum tubes

At the University of Pennsylvania, the key figure that steered, initiated and raised the idea of constructing an electronic automatic program-controlled digital calculating machine was John Mauchly. In August 1942 he privately circulated a memorandum among the team of instructors of the Moore School of Electrical Engineering about 'The Use of High Speed Vacuum Tube Devices for Calculating' [64]. This memorandum was considered lost; it was discovered in the late 1960s at the Moore School archive. This is crucial because many people like Goldstine raised an eyebrow when Mauchly claimed that he had published such a memorandum before January 1943 [65]. Before the memorandum was discovered, Mauchly reconstructed its introduction from the transcripts of his secretary; he sent it to John Grist Brainerd, the Dean of the Moore School. He added to it notes, including some rough drawings and detailed ideas as to the operation and the parts of this electronic difference analyzer as it was then called, namely, as an electronic automatic program-controlled digital calculating machine. Mauchly had objected to the name 'difference analyzer', as the term 'analyzer' referred then to an analog device, whereas what Mauchly had in mind was a digital device [66]. The memorandum contains an interesting account on the control unit and the possible applications of the device, such as ballistic calculations. A copy of the first draft report had been delivered on 2nd April 1943 to the USA Army Ballistic Research Laboratories (BRL) at Aberdeen Proving Ground MD. The authorship of the report is controversial, though it seems that it was the work of three people: Brainerd, Mauchly and Eckert. (The matter receives a comprehensive study in Appendix B below.)

Here I make use of the original written version that I unearthed before October 6, 1986 and before I had the opportunity to see the documents of the Honeywell vs. Sperry Rand trial at the Charles Babbage Institute at the

University of Minnesota at Minneapolis. The uncorrected version provides an illustration that supports my claim that an additional report existed, bearing the date April 8, 1943. The analysis of the trial documents make it is clear that the document delivered on April 2, 1943 was the first draft, as stated above. However, the literature also refers to another report by an anonymous author, bearing the date April 8, 1943. I thought then that this was an identical copy of the April 2, 1943 version, retyped by the Army omitting the author's name and changing the date to April 8, 1943.

However, eight months passed between the introduction of Mauchly's memorandum in August 1942 and the first controversy on it. But, from the moment of this first discussion of April 9, 1943, things started moving quickly. The reason was practical. Back then, the University of Pennsylvania housed the biggest mathematical computing center in the world. The center performed calculations of ballistics range firing tables for the artillery and for bombers. The center employed over two hundred persons, around one hundred of whom were graduates of mathematics and one hundred women soldiers employed as human calculators, trained especially for this task. Once the USA joined the War, the pace of development for new artillery pieces and types of projectiles accelerated sharply, and the workload was soon beyond the capability of the calculating center [67]. in September 1942, Goldstine was appointed as the representative of the Army in the University calculating center. After reading Mauchly's memorandum, he recommended and supported the development of a device according to Mauchly's ideas [68].

To show just how acute the limitations of human calculators became, let me mention that the Honeywell vs. Sperry Rand trial exhibits include letters from Goldstine to universities and colleges, asking them to direct their graduates to the computing center. The response to them was scant, particularly due to the lack of suitable qualifications.

The BRL staff were unusual in their openness to accepting new means, and quick in their decision-making, signing of the contract and starting the project [69]. The construction of the device began on June 1, 1943, and it was completed around November 1945 by carrying out an experimental run for the Manhattan Project. The name finally given to the device was 'Electronic Numerical Integrator and Calculator' (ENIAC). the minutes of a meeting held in April 1943 state that the name was given by Colonel Gillon, the commanding officer of the BRL [70]. The device was unveiled to the public on February 15, 1946. The events and reasons for it are discussed in Appendix B below.

While constructing ENIAC, around spring 1945, the ENIAC team members began working out the finishing details of its design. It had been decided, and rightly so, not to implement any ideas or changes deriving from work on ENIAC itself, but to apply them in the successor to ENIAC, the EDVAC, rather than amend the design of ENIAC. Ideas that crystallized during the building of ENIAC had to be shared, according to the contract with BRL. Brainerd was appointed as the head of the project, Mauchly as chief adviser and Eckert, then 24 years old, as the chief engineer.

Mauchly searched for faster and more accurate calculating methods for long-term weather predictions. He studied the calculating techniques that were then available. He could use a slide rule, and was well versed in mechanical calculating machines and punch card equipment. He worked with Bush's differential analyzer, and had developed his own electric harmonic analyzer. He was present at Stibitz's presentation of the complex computer (1940). It seems that he had heard about Aiken's Mark I. In June 1941, Mauchly visited Atanasoff at Iowa College in order to gain a better understanding of Atanasoff and Berry's device. And he was permitted to see it. It is claimed that he had also read the technical report and ideas attached to its development. So he could be in possession of a good picture of Atanasoff and Berry's 'computer' (ABC). Nevertheless, ENIAC employed decimal notation, unlike the ABC that employed the binary notation, the advantages of which Atanasoff explained explicitly in his memorandum of August 1940. I will limit myself to the above comparison of their basic properties, as more details on both are provided in Chapter 3 (sections on Mauchly, Atanasoff, Eckert and Berry). Mauchly examined all manners of new development trends in calculating devices, finally settling on electronic circuits.

What was special about meteorological calculations? And what was special about cryptography, in which he was also engaged for a while? What spurred Mauchly to develop this device? In the 1920s and the 1930s, an optimization approach prevailed in meteorology, and its main proponent was the British scientist Lewis F. Richardson, who reckoned that it would be feasible to predict a long-term weather forecast. In 1945, von Neumann also thought that the computer may be used to this effect. That was indeed one of the first projects of his computers. Richardson and his associates developed for this task a system of meteorological mathematical equations, and in spite of there being a rough approximation of weather patterns, they nevertheless permitted forecast with a reasonable probability. But this advancement stalled during the 1930s due to a lack of sufficient calculating power. Mauchly, Zuse, Atanasoff and Aiken were all working on that sort of mathematical problem, namely, the solution of large systems of linear algebraic equations. The calculating technique applied for these calculations rested on the difference in approximations and the need to decide the size of the error and the iterative methods. Nevertheless, what makes Mauchly's work unique was his multi-purpose approach as an inventor and developer. Mauchly provided a multi-purpose solution, based apparently on his wish since 1925 to find a general law for all possible conditions (see Chapter 3). He wanted to solve the problem of meteorology, but as a physicist he was aware that it was also feasible to adapt his idea to ballistics. As a pragmatist, Mauchly adapted himself to changing conditions, and despite being burdened and harried with meteorological calculations, he had no difficulty with the transition to ballistics.

Mauchly's partial training as an electrical engineer and physicist and his work as a physicist focusing upon meteorological calculations on the one hand, and the construction of electrical and electronic calculating devices on the other, provided him with a wide base of knowledge to compete in the development of the automatic program-controlled digital calculating machine. I must confess though, that I did not find any link between the design and development of ENIAC and the formalization of mathematics. Despite that, we have sufficient evidence to show that Mauchly as a student knew Boolean algebra. This knowledge seems to have become inert, as he did not apply it to the construction of ENIAC, even though binary notation and its technological possibilities are mentioned in several places in his reports of April 1943.

Chapter Four Summary

After this extended account of the events of the period 1935-1945, over three countries and eight diverse projects, what follows is an analysis of what it contributes to the answer to the following question: why did automatic program-controlled digital calculating machines develop in parallel, during the same period in three different places in the world? From the information and evidence presented throughout this chapter it becomes clear that different problems assailed the different developers and that the solutions that they gave were very different under different circumstances. From the events described it is possible to learn why the developers did what they did and to say that there is much in common between the various devices. Yet, as I have shown in all of the above cases, it is impossible to form a link between the formalization of mathematics and the introduction of these automatic program-controlled digital calculating machines. On the contrary, the opposite is the truth (as indicated in Answer 6 in the Summaries of Part I and Chapter 3); mathematical logic and anything linked with the formalization of mathematics, starting with Hilbert's programs of 1900 and 1928 (and even with Frege and with Peano before him) as well as the other mathematical logicians, had a marginal influence, if any at all, on the development of the automatic program-controlled digital calculating machines. It seems that the influence of mathematics was not so much from mathematics as a study or discipline, but rather quite simply in terms of mathematics as a quality of physical reality.

PART II SUMMARY

In this part I have concentrated on two main issues. To each of these issues, I devoted one chapter. In Chapter 3 I attempted to fetter out any unique and particular behavior patterns or properties in the individual and the collective profiles of this group of developers of automatic program-controlled digital calculating machines; in Chapter 4 I was occupied with the problem of why they did what they did and what the relationship was between their education, occupation, work and the formalization of mathematics and the appearance of the automatic program-controlled digital calculating machines.

In the survey of the individual biographies of this group, I concluded that there is nothing there that makes them unique or outstanding. However, one can distinguish easily that this was a different generation of inventors compared to what was previously known. All went through higher academic education. Yet that cannot serve as a sufficient explanation for their achievements or developments because, in the early 1930s, according to George W. Beahne (1935), there were in the USA seventeen universities and colleges that used punch and tabulating equipment for calculations in psychology, education, medicine, sociology, economics, agriculture, law, anthropology and linguistics. However, these means did not provide sufficient or comprehensive solutions for calculating purposes in the universities, as they were applied mainly for the analysis of data of any sort for administrative and management needs. Those that were used as desk calculating machines and analog devices provided a powerful factor in calculations. In addition to this, computing centers were established in some universities, like Columbia, Princeton, New York, Berkeley, Brown, Harvard, Pennsylvania, and MIT. In the UK, two calculating centers had been established already before World War I. One was at London University College, where Karl Pearson worked from 1903 on calculations in biometrics and later on the production of mathematical tables, and the other at the University of Edinburgh that was founded in 1913 by E. T. Whittaker.

The office-desk calculating machines became commonly used for scientific calculations in the mid-1920s. According to a report made in 1912 by the Englishman H. C. Plummer that includes the report from 1910 of the Royal Astronomical Society, the main means for astronomical calculations were mathematical logarithmic tables. Even in the 1920s, the mechanical calculating machine or other devices were not yet commonly used by astronomers. Only by 1928 did L. Comrie introduce a calculating machine in the Almanac Office of the Royal Navy. In 1919, Pearson edited *Tracts for Computers* while working in the Department of Applied Statistics (Computing Section) at University College London (by 'computers' he meant people who perform computations). Pearson explains that his book's aim is to fill the gap in the literature highlighted by the computers on his staff, who had 'been struck by the absence of any simple textbook for the use of computers'. In it he provides techniques to carry out interpolations for squares and mechanical integration. I found evidence that in Germany too, such computing centers for astronomical calculations existed in the 1920s—in Berlin and elsewhere— initiating probably at the beginning of the century. They applied calculating machines and included forerunners to Comrie's application of punch equipment.

As can be gleaned from intensive scrutiny of the individual biographies, there is nothing relevant identical about them, nor can one find any property uncommon to hundreds of other people in those countries. MIT in Cambridge MA had the same organizational concept and curriculum as Charlottenburg in Berlin, more so than those of the Moore School for Electrical Engineering at the University of Pennsylvania. What characterizes Zuse is that the design and construction of most of his components for the Z1 was done manually by his own hands without utilizing any previously existing equipment. Aiken, by contrast, incorporated only existing equipment, developing hardly any new component. Some developers provided a concept or idea utilizing existing instruments and developed the bare minimum by way of new parts to combine them, while others developed a concept and the new components needed to materialize the idea. Zuse, Berry and Eckert were under 24 years of age when they developed their devices. Mauchly, Aiken, Atanasoff and Stibitz were in their early thirties. Zuse and Atanasoff acted alone. Aiken, Mauchly and Stibitz acted as a team. Aiken, Eckert, Berry and Schreyer had broad formal electrical engineering education, while Mauchly, Stibitz and Atanasoff had only some formal training and practical experience in electricity and electronics. By contrast, Zuse had no formal training or knowledge in electricity and electronics. It is true though that engineers and physicists of the 1930s did have some considerable training in applied mathematics and in digital and approximation calculating techniques.

One can find some common factors and resemblance between Zuse's Z3 and Stibitz's and Bell's designs. The written sources from Zuse and Stibitz are also very much alike, in particular those concerned with binary notation and the advantage provided by utilizing relays for calculations. However, Stibitz's writings are deeper in their theoretical and mathematical logic base, resulting from Stibitz's background, educated as a mathematician as he was, in contrast with Zuse's education as an engineer.

Atanasoff also tackled the issue of choosing the preferable numerical base notation of his device, while Aiken troubled himself little in selecting a numerical base notation. Mauchly and Eckert explained later (1964) why they had not chosen binary notation and preferred decimal notation. The issue of a numerical base for notation is not even mentioned in Mauchly's (1942) memorandum. However, in the *Reports* (1943), there is a reference to the use of binary base and why a decimal base was preferred.

The summary of Part I has already treated the differences in shape, structure, and components integrated into the various devices. The evidence provided demonstrates that the similar biographical profiles of the developers, with their identical concepts, problems and exertions, did not necessarily lead to the development of identical or similar solutions. Moreover, even shared principles were not found.

It is most interesting that at MIT, Monroe, NCR, RCA and the tabulating equipment companies like IBM, all hesitated to enter into the production of such calculating devices. Indeed, RCA, NCR, IBM, MIT and even Bell (at the beginning of the War) worked on classified projects of calculating means based on electro-magnetic, mechanical and electronic components for fire control and decoding. Nevertheless, they did not see any sufficiently attractive project in the automatic program-controlled digital calculating machine to carry on its development. Moreover, even IBM, which was ready to support the development of the Harvard Mark I and financed other similar projects with great generosity, started its own similar projects only by 1944 and 1948. Even the Bell Company, after constructing the 'Complex Computer', did not carry on straightforwardly with developing and constructing automatic program-controlled digital calculating machines, but turned to the construction of analog devices. Stibitz states: 'They did not have interest in digital devices'. Even at MIT, the Rapid Arithmetical Machine project undertaken with the support of NCR, was shelved, strangely enough, with the outbreak of the War.

The passage to binary technology, of levers, electro-magnets and electronic switching circuits based on vacuum tubes, was not necessarily accompanied by the passage to binary notation or the wholesale abandonment of the wheel as the calculating and storage element; it is not obvious that the transformation to binary technology must be accompanied by the utilization of binary notation. This kind of transformation is not necessarily simple and explicit. It is not difficult to imagine the telephone dial, for instance, that enables the representation of ten states, in use as a component in a decimal calculating means, as were the Strowger switch and the later crossbar switch in automatic telephone exchanges. And, indeed, the IBM engineers, while designing Mark I, used such imitation of electro-mechanical relays for calculating and storage elements. The ENIAC team also used rings of ten vacuum tubes as counting and storage elements. Moreover, there was sufficient know-how in the 1930s to design office automatic calculating devices based on relays with electro-magnetic switches adapted to represent ten states like those of the teeth wheels in the common calculating machine (see, for example, Weygandt 1933). Indeed, at times, then, the telephone system used binary notation in decimal representation (BCD).

The biographical evidence on the developers of the automatic program-controlled digital calculating machines, in particular those discussed in Chapter 3, reinforces the claim that the appearance of the automatic program-controlled digital calculating machines did not derive from similar backgrounds or conditions. It is difficult to identify or to trace a collective profile for this group of inventors. Each of the developers had a different biography, with nothing relevant in common to the other developers.

Again, then, as to why they did what they did, and how if at all their education, deeds and occupations and the formalization of mathematics, their deeds, occupations and education influenced their development of automatic program-controlled digital calculating machines. Many had been troubled and occupied with similar problems. Many had similar or identical education and parallel occupations, and yet without the resultant development of any such devices. During the 1930s, many used calculating techniques based on calculating processes or programs. Most of the techniques were developed even earlier, at the end of the 18th century, such as those calculating techniques that the Austro-Hungarian applied mathematician, physicist and engineer Joseph Petzval (1807-1891) developed for the design and polishing of optical lenses (dioptrics) by solving large systems of linear equations. The number of equations depended on the level of approximation to be reached; an accuracy of five places after the decimal point required the solution of eight such equations, while an accuracy of seven places required the solution of twenty-seven such equations. Petzval was interested not only in approximate results but also in deviations from the ideal results. To this end he developed an algorithm, a veritable computer program, for human computers, guiding them, step by step, to solving such problems. And as mentioned above, Pearson also published a booklet with instructions for human computers, *Tracts for Computers* (1919).

From the analysis of the occupations of the developers of these devices, we may learn what manner of conundrums troubled them. For instance, Zuse, Aiken, Atanasoff and Mauchly strove to cope with the problem of calculations that were in essence systems of polynomials and large systems of linear or differential equations possessing a great number of unknowns or expressions. It is apparent that problems in meteorology, ballistics, crystallography, aerodynamics and other domains belong to the same category of calculating techniques, solvable by the very same algorithm. Stibitz and the Bletchley Park team confronted a different sort of problem. At Bletchley Park a scanning and sorting algorithm was required, while the Bell employees looked for a specific solution to problems concerning complex numbers.

Thousands of engineers, researchers and scientists exerted themselves. There was nothing unique in the problems they dealt with or in their occupations that made it necessary to provide exactly these kinds of solutions. Indeed, most of the solutions provided for unique problems were inherently analog. I have argued already that there was nothing unique in the education or biographies of these developers, relevant to the appearance of automatic program-controlled digital calculating machines. What characterizes these developers of those devices, despite their being and remaining unaware of mathematical logic and of the formalization of mathematics, is the very idea that information in general, not just within mathematics, can be expressed in a universal formal digital syntax, and that it could be manipulated in the widest sense.

World War II had a great influence everywhere on the transfer of these devices from just digital devices into alphanumeric devices. That information may be considered as a commodity, or resource, crystallized only in the late 1930s and early 1940. Already before 1940, this was manifest in the very crystallization of the theoretical concept of internal storage. Next came the realization of those concepts in diverse practical manners.

I conclude this discussion now with the following statement. The development of the automatic program-controlled digital calculating machines resulted partly from unique ideas and components, and partly by adapting existing ideas and components—although the dividing line between these two was not always clear. Among the new ideas that were significant for the developers of these devices is the treatment or manipulation of information. Zuse and Aiken conceived from the beginning of a multi-purpose device. The same is easily deduced about Aiken from his 1937 memorandum. Mauchly's 1942 memorandum also makes it plain that he was referring to a multi-purpose device. On the other hand, Stibitz, Atanasoff and the Bletchley Park team developed their multi-purpose concept gradually. I even harbor doubts as to whether Atanasoff thought at all in terms of any general purpose device, as may be concluded from Berry's letter to Richards of July 21, 1963. If we accept Eckert's claim (1976) that it was already possible to construct ENIAC (an electronic device!) ten years earlier than it was (in 1933 rather than in 1943) as all its components already existed at the early date, then it would likewise have been possible to construct an electro-magnetic or mechanical device even somewhat earlier, as such components existed and were already abundant many years before 1933. Excluding Zuse, who designed and developed the binary mechanical parts on his own, the rest of the developers utilized existing components, although at times they did improve one component or another.

Thus it emerges that the real transformation occurring from 1935 onwards in the *milieu* of developing calculating devices took place on three levels. The first was a preference of the digital over the analog approach in calculations in general and in scientific calculations in particular. The second was the adoption of the digital control based on a formal language that enabled the production of a desired sequence of instructions in that language; in short, a calculation program or a flowchart. The third level was expressed in the emergence of the concept that there was a need for a large and fast form of data storage: memory.

The question therefore is, what brought Mauchly (21st March 1925), to say something like

> 'It is my folly that prompted me, more than once, to formulate one rule for every situation, and to attempt to solve every problem by the same rule' [1].

This expresses an aspiration found also in Leibniz, Hilbert and others for the formalization of mathematics. What may result from this yearning for a formula, device, or universal machine? It seems to me that two major and competing fundamental approaches to problem solving appear throughout history, one that I shall dub the generality approach, and the other that I shall dub a partial or individual approach. In the generality approach, the aim is to find a model, principle or a general, multi-purpose pattern-formula that encompasses all possible problems and situations. By contrast, in the individual approach the aim is to reduce the solution to the bare minimum, to solve a single problem, to offer an *ad hoc* solution to a specific problem or to a group of formally identical problems. In the domain of calculating means, it is possible to distinguish these two approaches by two separate and distinct traditions. The origin of the generality approach in calculations can be traced, as I have shown earlier, to Leibniz (1679), proceeding *via* Babbage (1824) and Ludgate (1909). But, as I have also shown, the development of the automatic program-controlled digital calculating machines was undertaken, in most cases, in disconnection and in ignorance of the past, especially of Babbage's difference and analytical engines.

In the history of computing (and other domains as well), these two traditions, the general (comprehensive) and the individual (discrete), existed most of the time side by side and in parallel, sometimes dominated by the one and sometimes by the other.

From the available information we may conclude that during the 19th century the pertinent governed tendency was to provide general solutions in many domains. This started with general tool-making machines, the use of interchangeable spare parts, the setting of standards, the search for the most basic structures of mater and concluded with the formalization of mathematics. This tendency accelerated, and during the 1930s bore fruit, in the development of multi-purpose devices. I am aware that this explanation is somewhat strained, and I am not at all pleased, since the appeal to these two traditions seemingly challenges my conclusion that the development of these devices occurred in disconnection with the past. But when I reject the linear approach in the history of technology in general and the history of the computer in particular, that does not mean that the developers acted in a vacuum and shaped their contributions *ex nihilo*. I am aware that the developers began from previously existing components, means, technologies, techniques and background ideas. What I deny is that all comes about in a direct, unbroken, linear progression. I deny a compulsory linkage between a certain idea in the past and any conceptually related future outcome. What I reject, in short, is determinism: I do not believe that history is deterministic. From the study of the history of the digital computer, I learned that we do not have, as yet, a satisfactory explanation of developments of a certain calculating means exactly as it did, rather than otherwise. As another example, consider the development of the steam engine. Despite the extreme difference between these two developments, they follow surprisingly similar phases. Therefore, there is great latitude in alternate history speculation, although perhaps the phases may echo as in real history. In spite of our wish to make order, to explicate and understand the reasons of historical events, the answers and arguments provided until now are insufficient and unsatisfactory. What is important, then, is the provision of many answers by themselves, because their refutation enables the gradual restriction of the number of possible answers to the problem. It is my opinion that what is lacking in current research is that the number of possible answers provided is too small, and many more possibly controversial problems ought to be raised in the research. In this way it would be possible to avail ourselves of two major advantages: a) the release from prejudice as much as possible; and b) the systematic reduction of the number of alternative answers to the problem by refutation, thereby refocusing controversies on the remaining viable answers.

In summary:

a) One cannot relate any unique collective biographical profile to this group of developers of automatic program-controlled digital calculating machines that may provide evidence that there was something exceptional in these developers as compared to hundreds or even thousands of other people having many of the same qualifications, occupations, education and interests in the same or in other countries.
b) Even if these developers did adopt or base themselves on existing ideas of mathematical logic or those derived from ideas linked with the formalization of mathematics, then they reached these ideas independently, in ignorance of what was happening in this discipline.
c) The development of these devices was made possible exactly in the period 1935-1945, because, during the second half of the 1930s, these developers crystallized concepts according to which information is grasped as a commodity and in which it was possible to treat and manipulate it in the widest sense, like concrete entities. The developers also realized that the treatment and manipulation of information as a commodity, the digital representation, provided a great advantage over the analog representation, because numerals are symbols by whose means a formal language can be created.
d) Hence, additional examples of developers who exhibited this view of digital or alphanumeric information as a commodity are possible, other than what mathematical logicians such as Turing, Post and Church have envisaged. Most of the sources have not yet been researched, and some pertinent documents have been lost. This is known for the cases of Phillips (1936), Bush (1936), and Couffignal

(1938). Only a few people succeeded in materializing the idea of information as a commodity, and these worthy developers have been the subjects of this study.

PART III

THE PERIOD AFTER 1945

CHAPTER FIVE

THE MAIN ISSUE

What, then, were the unique conditions in the 1930s that enabled the integration and synthesis of those discrete means, ideas and techniques, surveyed here, in order to design something entirely different which I have named the 'automatic program-controlled digital calculating machine'?

Many answers to this very question are found in the literature, but none are supportable. The answers given simply do not explain the phenomenon of the simultaneous and parallel introduction of the automatic program-controlled digital calculating machines, specifically in the period 1935-1945, in Germany, the USA and the UK. The answers provided by others, and my arguments for their refutation, are as follows.

Answer 1

This is the readiest to hand and the most commonly accepted answer: the automatic program-controlled digital calculating machines were developed particularly during the period 1935-1945 in Germany, the USA and the UK, because it was a logical continuity to a long tradition of development of calculating devices. The problem was old; the interest in finding some way to mechanize calculations in order to ease the burden of calculations is ubiquitous. The mechanization of calculations is typical to each period: from stones for the Neanderthal humans to the computer experts of our era.

For evidence for this view scholars exhibit the abacus as a development of the period of 2500 years BC; the mechanical, digital calculating machine as a development of the 17th century; the difference and analytical engines, the tabulating and punch equipment and the analog calculating devices as developments of the 19th century; and naturally the computer as the solution given by the people of the 20th century to their computational needs

This is no answer. Why were the automatic program-controlled digital calculating machines developed particularly during the period 1935-1945 in

Germany, the USA and UK? This answer only allows for, but does not tell, for instance, why the abacus was developed in a particular era and not the slide-rule. Evidence makes it clear that the particular development of the automatic program-controlled digital calculating machines during the period 1935-1945 in Germany, the USA and the UK was not due to any continuity or sequential linear tradition, but that these developments took place, in most cases, in a disconnected manner and independently from previous events and accomplishments in this domain. So, for instance, the engines that Babbage (1791-1870) developed during the second quarter of the 19th century had marginal influence, if any at all, on the designers of those machines developed in the period 1935-1945. Aiken mentions the Analytical Engine (1834) and the Difference Engine (1822) and other calculating means in the brief historical introduction to his memorandum (1937). Evidence seems to suggest that Aiken was aware of, and influenced by, what the common historiography terms as traditional 'computer pioneers'. Not so.

This answer is easily traced to Aiken's (1937) memorandum:

> 'The desire to economize time and mental effort in arithmetical computations, and to eliminate human liability to error, is probably as old as the science of arithmetic itself.' [1].

He then proceeds in the linear tradition *via* Napier, Pascal, etc., through Babbage, Scheutz, Grant and Ludgate until IBM's tabulating equipment, which will enable 'the construction of an automatic calculating machine specially designed for the purpose of mathematical sciences' [2]. It is evident from Aiken's proposal that he called for combining available commercial calculating equipment, such as that of IBM, for scientific calculations. His interest was in obtaining new calculating properties from the proposed device. This could be achieved by adopting commercial equipment and providing greater flexibility and general purpose characteristics by incorporating it under a switch board and sequential control. Zuse, in Germany, only learned about Babbage by 1937, which was already after he had developed his Z1 (1936), and that only after applying for a patent for the Z1 in the USA. Other developers such as Stibitz (1937) at Bell Laboratories, Atanasoff (1936) at Iowa College, Mauchly (1941) at the University of Pennsylvania, and the team from the cipher school of the Foreign Office at Bletchley Park in the vicinity of London (1941-1943) worked in total ignorance of Babbage's work.

This answer does not explain that logical process by which the transfiguration from one invention to another takes place, and why these devices were developed in parallel, exactly in the period 1935-1945 in precisely Germany, the USA and the UK, and not in China, for instance.

Barring the abacus, quipu, slide-rule, and Napier rods, the tradition of digital and analog calculating devices rested entirely on the wheel or gear. By contrast, the new devices rested on switching circuits. The switch is an apparatus enabling two extremely distinct opposing states (binary). The switch could be constructed by using mechanical, electrical, electro-magnetic, electronic and other technologies. The integration of several switches into a Boolean logic circuit (the logic developed by George Boole in 1854) makes possible its application as a calculating or storage element. It was found that the binary notation merely provided a great technical advantage. For example, the storage capacity in binary base notation is 3.34 times larger than in decimal base notation. It is of course technically easier to produce two opposing states than ten. Even though, in some of the automatic program-controlled digital calculating machines developed during the period 1935-1945 in Germany, the USA and the UK, binary notation was adopted, and the technology utilized was binary and founded on binary switches, from the evidence provided, it is not only clear that this answer is not entirely relevant to the problem under debate, but besides that, it is false. I have shown that these devices, developed between 1935-1945, departed from other devices included in the linear historical tradition of calculating means, and that these devices were designed and constructed in ignorance of previous traditions of calculating means. As for Aiken's memorandum (1937), at best it can be seen as an exception, though, putting it bluntly, I reckon that Aiken just used the historical introduction to his memorandum (1937; it also happened to be copied in Aiken and Hopper's 1946 paper, see below) from a book and he was totally unaware of the significance of Babbage's work [3]. Only later (1942) did Aiken adopt Babbage as his spiritual mentor (see Part II).

If, however, it is possible to find some typical characteristic of these automatic program-controlled digital calculating machines, then it would be found, and only so, in their breaking from earlier traditions of calculating devices, in which the wheel or gear was the exclusive means of automating calculations, into a new paradigm in which the two state switch combined by logic circuits was used as a calculating element and as a storage element. Until the introduction of Shannon's dissertation (1938), the utilization of these logic circuits was accomplished intuitively by trial and error in total ignorance of Boolean logic.

Answer 2

The automatic program-controlled digital calculating machines were developed exactly during the period 1935-1945 in Germany, the USA and the UK because various people at random developed the ideas and the variety of tools that were then found to be appropriate for this type of device as a hobby.

This answer is my own. It serves for an analysis of the likelihood of discovery by chance. The so-called 'eureka phenomenon' (from the Greek *'eureka'*, meaning 'I found (it)', the legendary exultant exclamation of the excited Archimedes running naked in the streets of Syracuse) appears in secondary sources such as Gardner (1982). The discovery at random is better related to Atanasoff, and hardly to Stibitz.

This answer serves as *reductio ad absurdum* for an argument so inane because of the eight automatic program-controlled digital calculating machines under consideration; only the case of Stibitz can be considered, on the face of it, as an unintentional surprising discovery. He constructed as his hobby on a weekend vacation a binary adder (a calculating apparatus for adding numbers) made of salvaged telephonic electro-magnets. His superior at the Bell Laboratory took sufficient interest and wondered if the binary adder could be used for complex number calculations. (The role of this sort of question in the invention process is rated in the summary of the introduction.) The Bell Company set up a special project team (1938) for this purpose and, by October 1939, the Bell Model I was completed and christened the 'Bell Complex Number Computer'. This model's operation was publicly demonstrated for the first time in September 1940 before the American Mathematical Society Conference in Hanover NH, and was operated from its location in New York by remote control from a teleprinter installed in Hanover.

Atanasoff's 'invention of the idea of a computer' is described as a 'eureka' phenomenon, facilitated by two glasses of bourbon and soda, in a forsaken tavern in Moline IL, during a stormy night in winter 1937. Atanasoff succeeded in crystallizing the concept of his calculating device, particularly the idea of rechargeable memory. His account suits the 'eureka' mold of Archimedes sitting in his bath and discovering his law; Newton, the falling apple and the law of gravitation; the fire splinters and the Benzoic ring's chemical bond structure of August Kekulé; and other such discoveries. But when this 'eureka' phenomenon is analyzed carefully and critically (as in the cases of Archimedes, Newton, Kekulé, or like T. P. Hughes in the case of Tesla, inventor of the alternative current motor), it is apparent that it was not a discovery by chance or at random; rather, it is the culmination of a lengthy and persistent thinking process. Thus the reduction of the development of the automatic program-controlled digital calculating machine as a phenomenon solely due to fate, chance or randonmess is entirely unsupportable and even ludicrous.

Answer 3

The automatic program-controlled digital calculating machines were developed exactly during the period 1935-1945 in Germany, the USA and the UK due to influence from and the copying and application of methods from automation, management and assembly line production in industry into the areas of engineering and scientific calculations. This answer is very common in the computer science literature, although it is not as widespread as Answer 1. The reason for its popularity is connected with the linkage between the development of the computer and automation equipment, meaning that the Hollerith and IBM punched card tabulating equipment is considered by the computer science community as the beginning of the automation era, as many automatic tools were controlled and operated by punch cards or tape. This answer has also been popularized by the great involvement of IBM in the research of the history of computers, according IBM a favored historical standing far beyond what is deserved.

This answer addresses only one part of the question. This relates to simultaneous and parallel discoveries in Germany, the USA and the UK exactly in that time period, which, besides, is historically falsified. The reduction of any complex process into a series of elementary operations is inherent to the age old division of labor in society as extolled in Adam Smith's *The Wealth of Nations* (1765). And automation can already be found, for example, in the music box and in the automata of the 16th century and even earlier, indeed in the remarkable automata of the legends of the ancient world. Even the punch card and punched paper tape have been known since about 1725, and their application as a calculating and information storage means was taken from the Jacquard loom (1804) by Babbage for his analytical engine (1834) and by Hollerith (1880) for statistical census information processing. All this has made for fertile fodder in the steampunk genre of literary alternate history. Indeed, why did it not all happen until so much later? The punched paper tape had already been utilized as a control means for industrial equipment and in musical instruments of all sorts during the second half of the 19th century. There is also evidence that the punched paper tape was incorporated even earlier in player pipe organs activated by pressurized air, preceding the application of the silk draw loom adopted by Basile Bouchon (1725). The punched paper tape was also utilized by Charles Wheatstone (1858) in his automatic telegraph, which became very common once the Baudot code was introduced (1874). It was used for the first time when a code with a fixed number of signals was applied, enabling the representation of 32 varied symbols. The automation of the telephone was influenced by the telegraph's electro-magnetic relay, with the introduction of the automatic electro-magnetic exchange (1892). The denotation 'electric brain' had already been given in the 1930s, precisely to the telephone exchange [4].

By contrast, the assembly-line (then known as 'Taylor's scientific management') was introduced into industry in the late 1920s. In the assembly line, as it was applied in practice, the idea was to divide a complex production process into a sequence of measured simple elementary operations to be performed by workers with no qualifications. This idea had already been adopted earlier by Adam Smith in France (1795) and by the mathematician Gaspard de Prony (1755-1839) who used it for the calculation of decimal (metric) mathematical tables.

In not one of the examples of automatic program-controlled digital calculating machines developed in the period 1935-1945 is evidence found to the effect that there was any influence or copying of ideas from automation, management or the assembly line to the domain of scientific or engineering computing, as claimed in the body of this answer. Aiken (1937) proposes an automatic calculating machine that would function in a sequence of iterative operations, based on IBM equipment with minor modifications and adjustments, if it was combined with electrical wiring and controlled by an imitation of the manual telephone exchange connecting plug-board. In his words,

> 'Fundamentally, these features are all that are required to convert existing punched-card calculating machines such as those manufactured by the International Business Machines Company into machines specially adapted to scientific purpose.' [5].

Nevertheless, there is nothing in Aiken's proposal to ratify the validity of this answer, since the plug-board control was hardly utilized in industry. Moreover, before turning his proposal to IBM, Aiken tried his luck at the Monroe Company, a known producer of mechanical calculating machines which turned down his proposal straightaway. Evidence suggests that by 1935 Aiken had developed two electro-magnetic machines for the solution of equations, without being influenced by the events taking place in industry. Even the automatic control developed by Zuse (in all his models), Stibitz (from his second model in 1942) and the Bletchley Park machines in the UK (1941-1943) utilized punched paper tape, as Baudot had used it in telegraphy. In addition, the devices of Atanasoff and Mauchly, in which the punched card was adapted for control, storage and the input/output of data and instructions, has no pertinent relation to industry.

Therefore, the attempt to relate the development of these automatic program-controlled digital calculating machines to automation, management and industry, as made in this answer, is historically refuted. Babbage and Hollerith adopted the punch card from Jacquard's loom. Nevertheless, as I have already argued, Babbage's influence on the developers of these devices in the 20th century was marginal, if it existed at all. But even Hollerith's influence, by means of his punch equipment, that was abundant and common during the 1930s, was also only partial and can mainly be seen in the development of Aiken's machine. In other devices such as ENIAC, for input and output purposes, IBM's standard equipment was used in order to save research and development time. Hence, it can clearly be concluded that this answer is futile.

Answer 4

The automatic program-controlled digital calculating machines were developed exactly during the period of 1935-1945 in Germany, the USA and the UK because of the need for more sophisticated control, test and simulation means, as a result of the introduction of various more expensive systems in industry and in scientific research.

This answer says how the automatic program-controlled digital calculating machines were developed, yet in entire disregard for the overall problem, in particular the simultaneous discovery in the period 1935-1945. It is historically refuted. In principle, any automatic program-controlled digital calculating machine can serve as a simulator. And, indeed, the Bell Model II, the Relay Interpolator (1941), ordered by the American armed forces, was intended for utilization as a checking device or emulator for fire control systems. Even the Bell Model III (1942) was constructed to serve as a simulator for training anti-aircraft gunners. However, these two models were merely improvements upon Model I, designed for the solution of problems with complex numbers. Hence, people at Bell were well aware of the general purpose capacity of their device, and so they developed Model V in 1945 as a general purpose device. Zuse had developed a general purpose device from the very beginning. First, it was an experimental mechanical pilot model, the Z1 (1938); later, the mechanical calculating unit was replaced by an electro-magnetic unit, and it was renamed Z2. Zuse's Z3 (1941) was apparently the first practical general purpose device in the world, utilized in the aircraft industry for aerodynamics examination calculations. Subsequently, Zuse founded his own firm and constructed two models (the S1 and S2) designated to test the vibrations of wings of aircrafts and their influence on metal fatigue. Yet even these later developments rested on Zuse's previous work on Z1, initially intended to be a general purpose device.

From the known evidence and the information provided above regarding the other automatic program-controlled digital calculating machines developed during the period 1935-1945, I conclude that they clearly contradict this answer. Hence, I conclude, these devices were not developed due to any need to test or to simulate any instrument in industry or in scientific research. This answer should be considered refuted.

Answer 5

The automatic program-controlled digital calculating machines were developed exactly during the period of 1935-1945 in Germany, the USA and the UK because, in the 1930s, new concepts of mathematical logic crystallized, resulting from answers provided by Gödel, Church, Post and Turing on problems that Hilbert's program had set (1900 and 1928), enabling the application of universal and general purpose principles in the calculating devices.

This answer is also popular and widely accepted in research, particularly among computer science scholars. It is very easy to refute and to show that it is futile because, curiously enough, there is no direct evidence to the effect that mathematical logic influenced or led in any way to the development of automatic program-controlled digital calculating machines. Moreover, this answer makes no reference to the issue of simultaneous discovery at that particular time and in those particular countries. At most, what could possibly be related to this answer is Turing's famous paper (1936), in which for the first time the idea is raised, of a universal machine, a machine capable of performing a human computer's functions. And indeed, it is here that the idea of general purpose is first introduced and in utmost urgency. But all that was not known to all those involved then in the development of the automatic program-controlled digital calculating machines (see also Part II). That being said, of all the mathematical logicians, Turing was the only one who had participated personally in the development of such a device, the 'Bomb' (1941), an electro-magnetic deciphering device. Various scholars have tried to connect the development of the 'Bomb' with Turing's famous work of 1936. It was computer science scholars who connected Turing's universal machine with the computer due to their general-purpose concept. However, this is anachronistic. From our modem knowledge of the events, it is obvious that Turing's 1936 paper did not arouse the watershed moment in the development of automatic program-controlled digital calculating machines that scholars longed for in hindsight. The influence of mathematical logic on the development of the computer was meaningful only after 1945, a matter beyond the scope of this study. Nevertheless, relating it to the 1930s is anachronistic.

There is indeed some evidence from a single trial, in the UK in 1938, to construct an electro-magnetic Turing machine resulting from Turing's 1936 paper, but it was cut short at a very early stage of design because the developers realized that the device would be impractically slow for their needs.

Hence, until new evidence is disclosed concerning the development of these devices in the UK during World War II, this answer remains unsupportable according to currently known history, if predicated upon the premise that Turing's (and his colleagues') contribution to the development of the 'Bomb' had roots in his 1936 paper.

Answer 6

Similar automatic program-controlled digital calculating machines were developed exactly during the period 1935-1945 in Germany, the USA and the UK, despite resulting from different problems challenging the various developers.

This is a partial answer, since it is a collection of several possible answers, each of which may serve as a full possible answer. If different problems produce similar devices, then each of these problems by itself must independently suffice to cause their development. The answer offers no reasoning as to why these devices were developed precisely in the period 1935-1945 and in those countries. If this answer is correct, why then were only six similar devices introduced and not more? It allows for the assumption that in the 1930s more than just six people were troubled with such problems that occupied the various developers. It also does not provide any explanation of any of the characteristics of those problems and how they led to these sorts of calculating devices. Finally, the answer does not relate or provide any criteria for parameters of identity or similarity. Putting that aside, the logical distinctions and criteria between identical or equal and different are obvious. For my part, I choose to view similarity as used in geometry: similar figures have identical forms but different sizes. For the present discussion this will be expressed as different scales of their characteristics. But even after clarifying the generality, the specific particulars of 'identical' or 'different' in automatic program-controlled digital calculating machines may still require further inquiry.

In discussions of previous answers, I argued that these devices varied in other ways: in technologies utilized, in base number representation, in structure and in the composition of components. Without going into detail (for a detailed survey see Part II), different types of problems engaged the various developers of these devices and each of them, with the exception of those of Zuse, were developed and constructed for defined ends. Nevertheless, to some extent the other developers were also aware of the general purpose capacity of their devices, but only in retrospect. Still, it is possible to find a common denominator for all these automatic program-controlled digital calculating devices, of which most of the developers were aware: specifically, it is Newton's method of differences. They reiterate calculations performed at predetermined approximately estimated intervals, by means of which the extent of the accumulative error could be determined.

Hence, this answer is incomplete, since on the basic level of design these devices varied one from the other, yet in the method of performing calculations we find between them some sort of common denominator. Naturally, subsequently we know that all of these devices match the criteria of the automatic program-controlled digital calculating machines, which is why I discussed them, as I have stated repeatedly. This answer remains incomplete, since it may be that each separate argument, in the problem that occupied the mind of an independent developer, sufficed to inspire the development of such devices, or that all those separate arguments together were those that served as the cause for their development. Hence, it is allowed here to proceed into two additional opposing answers, examining our question from inverse viewpoints. The first answer argues that in this particular period, due to the different problems troubling the developers, different devices were developed that subsequently were classified as identical. The second answer argues that identical devices were developed because the problems confronting the developers were identical. Thus, this answer is refuted down to its roots.

Answer 7

Diverse and totally different automatic program-controlled digital calculating machines were developed during the period 1935-1945 in Germany, the USA and the UK because the problems confronting the developers were different, and only subsequently were these different devices classified as identical discoveries because of new view developed in hindsight, connecting them conceptually and abstractly.

This is a vague and unclear answer. Admittedly, there were many differences between the various devices. Yet the extent of their differences is hard to measure. Different technology was applied in the construction of different devices; for example, mechanical, electro-magnetic or vacuum-tube technologies. There were also differences in the dimension, size and form of these devices. The Zuse Z3 was of the size of an upright piano, whereas ENIAC and the Harvard Mark I sprawled over a vast area and weighed several tons each. The devices also varied in their numerical base notation. The devices of Zuse, Bletchley Park and of Atanasoff operated on binary representations. In contrast, the devices of Stibitz and Bell utilized the bi-quinary (two and five) combined base notation, while ENIAC and the Harvard Mark I operated on decimal base notation. As for the control techniques, in some of the automatic program-controlled digital calculating devices, perforated paper tape control was implemented (Bell, Zuse and Bletchley Park), some adopted the punched card as a control means (Atanasoff and ENIAC), and other machines applied the switch-board plug control, like that in the manual telephone exchange, the Harvard Mark I, ENIAC and the Colossus at Bletchley Park. The Harvard Mark I that Aiken developed at IBM imitated the toothed cogwheel gear mechanism with electro-magnets, while in the rest of these devices calculations were performed on Boolean logic electrical switching circuits designed by trial and error, most of them in complete ignorance of Boolean algebra, let alone the famous Master's thesis of C. Shannon (1938) and the Japanese Nakajima (1936). The primary sources indicate that at least Stibitz had some knowledge of Shannon's work, but only after he had developed his idea. This holds also for the people at MIT working on the Rapid Arithmetical Machine and also ENIAC team.

Nevertheless, conceptually all these devices belong to the same category since they all meet simple criteria; if they were totally different and did not serve to solve identical problems then it would not be possible to determine such a common denominator for them. This is all despite the fact that, in the period 1935-1945, no such criterion for this type of device was possible, and the sole expression as to their uniqueness was to be found in their naming. For instance, the Harvard Mark I was called the 'Automatic Sequence Controlled Calculator'. That is to say, an automatic calculating device having a sequence control mechanism. Likewise, ENIAC (Electronic Numerical Integrator and Computer) means a numerical calculating device utilizing electronics for its function and applying the integrating principle for calculations, although the original name proposed for the device was the 'Electronic Difference Analyzer' (April 2 and 8, 1943). Zuse, in his patent application (1936), describes his device as a 'method for independent (automatic) execution of calculations with the aid of calculating machines'. Stibitz, meanwhile, at the Bell Telephone Company, called the Bell Model I a computer ('Complex Computer'), a term related in those days to a human computer, a human. Mostly women entered the profession of performing calculations of any sort in engineering or science. (As to the development of the term, usage and concept of the computer that we are familiar with today, see Appendix A.) Even though most of the development of each of these automatic program-controlled digital calculating devices proceeded in ignorance from each of the others, although some were aware of Stibitz's Complex Computer and Aiken's Mark I, these devices were nevertheless later classified as identical conceptual discoveries. We already know (see Chapter 2) that the various developers did not follow any preconceived common program that might have paved the way for them by some common spiritual mentor. This answer, though paradoxical, still merits serious consideration.

Without tangibly identical characteristics or even an identical strategic thrust and guiding intent—in a word, teleology—this retrospective categorization is a clear case of a meaning created in the mind, not in the world, a hypothesis, an unfounded conjecture, to be subject only later to critical preference and empirical reality testing. What bearing can it then have on reality? Truth; and truth is correspondence between reality and assertions. What is the nature and path of such correspondence? Knowledge is awareness of the truth. Thus truth can be understood. And understanding can be abstract. Categorical reasoning can indeed yield understanding in correspondence to reality. Thus there is nothing to rule out categorization from coming to light only after the events from being true. It happens all the time. But the questions remain empirical. Do the devices in question all fit within the category? Is the assertion true for each of them? We assume that our observations are true. Does this explain how or why this is so? No it does not. This is no causal explanation, only a clearer definition. But even that is contributive. According to Karl Popper, the truth of hypotheses is unknown but we hope to approximate it by testing and trying to refute them.

Answer 8

The automatic program-controlled digital calculating machines were developed during the period 1935-1945 in Germany, the USA and the UK because the limitations imposed by conventional calculating devices provided an incentive to the various potential developers to seek new directions in order to overcome these hindrances.

This is a controversial answer, since it does not detail those limitations in contemporary conventional calculating devices that might be the cause, pretext or impetus for the various developers to improve and design these new devices. Moreover, the answer does not provide details of the reasons for the developers' discontent with contemporary or earlier calculating devices. There is either no explanation of such an incentive to develop this type of device not having materialize, say, in the Soviet Union, Italy, Switzerland, Japan, France or elsewhere, where extensive production of conventional calculating devices was also underway.

Of all the devices discussed here, possibly Aiken's Mark I and possibly also Atanasoff's device fit this answer to some extent. According to this explanation, Aiken found a way of overcoming the limitations imposed by the common IBM punch card tabulating equipment *via* an electrical communication system under one control unit, thus achieving a new form of calculating device—the automatic sequential calculating machine. This was not the case with other developers of these devices. Zuse, for instance, who could be considered as a professional inventor, did not turn to the design of the Z1 due to any incentive to improve the limitations of any previously existing conventional calculating device. His development did not follow any continuous process out of discontent with any hindrances of a common existing device and its improvement or amelioration to a new or different type of device. Evidence indicates that his was a procedure that rested on totally different experience, namely, the experience accrued by developing a device that had to incorporate an independent concept, in ignorance, unawares of all that had previously happened. Subsequently, Zuse's new device exhibits a direct passage from manual calculations to mechanized calculations, consciously skipping over or bypassing the previously existing calculating devices. This happened in other cases as well, except for the case of Aiken. In the UK, the development of the 'Bomb' was also carried out by directly copying manual procedures into a mechanization, although they acquired some guidance by following the Polish 'Bombe'. And Stibitz, who was not a professional inventor, developed for fun his binary electro-magnetic adder as a hobby. Only later, due to an interest that his superior Dr. Fry showed, he implemented it in the Complex Computer. Mauchly and Eckert, initiators and developers of ENIAC at the University of Pennsylvania, eventually acted as professional inventors and as entrepreneurs who worked within the system. Mauchly first developed analog calculating devices, then moved into the development of digital calculating devices based on vacuum-tubes (1936). It was for him a hobby transformed into a lifetime career. Like Aiken, who tried his luck first with Monroe and subsequently interested IBM in his proposal, when Mauchly reached the conclusion, with Eckert's assistance, that it was feasible to realize his idea to utilize vacuum-tubes for high-speed calculations (1942), he too looked for an investor or an entrepreneur and found it in the US Army's Ordnance Department, whose people were at that time keenly interested in supplying mechanized calculations to meet high demand. At Iowa College, where a long tradition of applying calculating devices based on IBM's tabulating and punch equipment had existed since the 1920s, Atanasoff, like Mauchly, also began with the construction of an analog device (1934). He moved immediately to the development of a digital, binary electronic calculating device, having been influenced by an article of 1934 that discussed the feasibility of utilizing the binary notation and vacuum-tubes for the counting and storage of data [6]. The device, designed by Atanasoff and his assistant Berry, was highly original and in deviation from the common trend of conventional calculating devices. Unfortunately, Atanasoff was just not cut out to be a professional and dedicated inventor. He abandoned the development of his device by August 1942 when it met with still unresolved technical difficulties, mainly with the control unit, and made other commitments instead. However, he returned to deal with the issue some time later in the 1960s in a controversial trial on the validity of the ENIAC patent rights, Honeywell vs. Sperry Rand (1967-1974). This has already been treated in an earlier chapter concerning the historiographical impact of sheer ego.

In some cases, automatic program-controlled digital calculating devices developed during the period 1935-1945 were admittedly introduced because of the existing limitations in the conventional calculating devices, and discontent with these limitations encouraged and spurred the various developers to seek new ways of overcoming these shortcomings. Admittedly, Atanasoff, Aiken and Mauchly expressed discontent with the then existing common calculating means. This was not the case with Zuse, Stibitz and the developers of the 'Bomb' in the UK. Zuse had only his own transitional devices to inspire interim dissatisfaction. With the exception of Aiken, this is indeed just not how the tale unfolds.

Answer 9

The automatic program-controlled digital calculating machines were developed during the period of 1935-1945 in Germany, the USA and the UK because they were needed for fast and precise calculations in science and engineering, namely in physics, mathematics, astronomy, etc.

This answer appears in the history of computing literature, and is a part of the linear tradition. Writers like L. Comrie and W. Eckert are the promoters of this view. It is controversial, because it does not contain an explanation of how the need for a specific sort of calculation may bring about the development of these automatic program-controlled digital calculating devices and not any different and unique type of device capable of providing sufficient solutions to the problems of the time, for example analog calculating devices. Evidence may offer partial support for what this answer claims, yet its refutations are devastating. In addition, this answer makes no reference to the issue of the parallel and simultaneous introduction of the devices in that period and in those countries, even in isolation.

There was no such need, as this answer suggests, for faster and more precise calculations in science and engineering. In the period 1935-1945, the level of precision required for practical engineering needs was at the scale of 0.001 (one thousandth) of a millimeter. This level of precision was easily and quickly attainable by common contemporary digital and analog calculating devices that were then relatively easily available in the market. Even the long slide-rule (with a length of 30-40 centimeters) could provide a quick and accurate solution to this kind of problem. Therefore, history obviously refutes any claim for such a need.

Consider then the need for such devices for scientific calculations. Here, on the face of it, Aiken's proposal (1937) serves as evidence for such demand to develop this type of device, because there it is stated that:

> '...the need for mechanical assistance in computation has been felt from the beginning of science, but at present this need is greater than ever before. The development of the mathematical and physical sciences in recent years has included the definition of many new and useful functions, nearly all of which are defined by infinite series or infinite processes. Most of these are inadequately tabulated and their application to scientific problems is therefore retarded.
>
> 'The increased accuracy of physical measurements has made necessary more accurate computation... Many of the most recent scientific developments, including such devices as the thermionic vacuum tube, are based on

> nonlinear effects... The only methods of solution available in such cases are expansions in infinite series and numerical integration. Both these methods involve enormous amounts of computational labor.'

Aiken added that the developments in wave mechanics, the theory of relativity, ionosphere study, mathematical economics and radio and television communication systems raise computational difficulties with which physical, astronomical and mathematical sciences face. Then he concludes:

> 'All these computational difficulties can be removed by the design of a suitable automatic calculating machinery.'

Everything Aiken wrote in his 1937 proposal should be examined with great care and considered just as a sales-pitch, particularly its historical introduction. Admittedly, the device Aiken constructed, Mark I, was mainly used for ballistic calculations, a certain type of practical scientific and engineering calculation applying partial differential equations for the USA Navy, mainly for ship-planning, as well as the deduction of mathematical tables. Yet none of these activities were concerned with scientific calculations. The tables for Bessel Function were calculated some time later, hence its nickname as 'Bessie', the Bessel Machine. It is possible that the war prevented Aiken from applying his machine for the purpose named in his 1937 memorandum. Yet even his later models—Mark II in 1947 and Mark III in 1949—were devised for the Army for ballistic calculations. Moreover, during the period 1935-1945, the scientific and economic establishment in general was interested in a calculating means that would produce numerical mathematical tables of various kinds quickly, efficiently and accurately, in the tradition of the 19th century, with little involvement or entanglement in the connected logic or calculating means. Zuse, Atanasoff, Mauchly and other developers of this type of device sought more effective and efficient ways and means of computation to carry it out. This is one of the essential differences and changes in concept that characterize the new devices.

Not one of these machines developed then had been designated in advance to compete with problems of physics in general and with problems in quantum or atomic physics in particular. On the contrary, during the 1930s and even earlier, single purpose tools were developed with the sole objective to trace, count and control the phenomena of atomic or elementary particles. The first application of an automatic program-controlled digital calculating device for atomic physics, was in November-December 1945, for Los Alamos (the Manhattan Project's hydrogen bomb) during the experimental run of ENIAC at the University of Pennsylvania. And ENIAC was intended to produce firing tables for the artillery and bombers of the USA Army and Air Force. For solving problems in mathematics, chemistry, meteorology and astronomy, special and unique devices were developed. An example for a single-purpose scientific end is the 1908 Geiger counter or Geiger-Müller counter. Other examples are, the electro-magnetic sieve of 1926, in Berkeley, California, the photo-electric sieve built by Lehmer by 1932 to determine various series of Diophantine equations and, in chemistry, a device to determine structure, distances, and spectrum reflection in various crystals. One of these devices was constructed by Berry, Atanasoff's assistant.

To conclude the criticism of this answer, even if we do not disregard Aiken's proposal of 1937 and take it at face value, and if we also consider the test run on ENIAC as a practical application for calculations in physics, even then, in the cases of the rest of the machines described here, history still contradicts the answer that the automatic program-controlled digital calculating devices were developed as a response to the need for fast and accurate calculations in the exact sciences and engineering.

Answer 10

The automatic program-controlled digital calculating machines were developed during the period 1935-1945 in Germany, the USA and the UK because the body of knowledge in those countries was then at a similar stage of development, leading the various developers to ask similar questions and arrive at similar solutions.

This answer rests on Robert Merton's explanation of the phenomenon of simultaneous discovery. This is a common answer in the semi-professional literature. In this approach are elements borrowed from the biological evolution of natural selection, in which the environment influences the evolving entity. It is a sort of gentle and moderate concept of inevitability. Thomas Kuhn seems to agree with Merton. In discussions of simultaneous discovery, Merton and Kuhn deny that they are evolutionists. Answers 6, 7, and even 10 stand in acute contrast to this denial. This is crucial. Answer 6, presented by myself, is the claim that under similar conditions different solutions to the same problem appear. Answer 7, provided by Elkana, argues that in different conditions different inventions appear that are subsequently viewed as identical. This answer (that follows Merton, incidentally), is the view that in similar conditions similar things happen. There is also a fourth possibility that will not be discussed here: in different conditions entirely different things will be created, but which nevertheless still provide a solution to whatever is the problem at hand.

Answer 10 is controversial as it is difficult to set criteria for identity or similarity, as was already explained in the discussion of Answer 6. Also, we do know that the body of knowledge in other countries was similar to that in the countries where the invention took place, the countries where this type of device was not developed. Answer 10 does not provide an explanation of how it occurred that just six 'scientists' (Merton considers science any science-based technological invention, such as the invention of the telephone) and no more succeeded in developing exactly this particular type of device. There is also no explanation of the kind of conditions, of any identical body of knowledge, that generates incentives to scientists to ask similar questions, let alone how this passage from similar questions might lead to similar answers. Is this transition accomplished by an identical uniform process or by different ones? If answer 7 is true, why then, only six such devices were developed and not many more or a few less? The body of knowledge in Austria, Switzerland, Sweden, Denmark and the Netherlands was the same as in Germany. Similarly, the body of knowledge in France was the same as that of the UK. Why, then, in France, Denmark, etc. was this type of machine not developed?

I have shown in my discussion of previous answers that these automatic program-controlled digital calculating devices differ in many aspects from one another and that the personal and general backgrounds of the developers were different. Zuse, for example, was a civil engineer in the aviation industry, and independently developed his Z1 and Z2 at his parents' home. The problems that he had faced as an engineer concerned repeating calculations (iterations) of material strength and of statistics. In the UK, the development of the 'Bomb' was influenced partly by the Polish 'Bombe' (1938) and the development of the Colossus (an electronic decoding machine) was influenced by the limitations of the electro-magnetic and electronic Bomb of Heath Robinson. The UK developments were carried out by widely mixed teams of mathematicians, logicians, physicists and engineers—electrical, telephone and radar. Stibitz, a mathematician, constructed a binary adder as a hobby which was implemented in the Complex Computer. By contrast, Atanasoff was a physicist with a background in electrical engineering, who had an interest in solving large systems of linear algebraic equations. Aiken was a physicist interested in problems with polynomials, who later became a practical mathematician. Mauchly studied for two years in electrical engineering, graduated as a physicist, and his interest was in meteorological calculations. Eckert, Mauchly's partner in invention, graduated as an electrical engineer and specialized in radar.

If there were identical conditions in the various parts of the world, then why did Zuse have such difficulty in finding investors or entrepreneurs or support for his invention within the framework of the German establishment? In the UK the initiative for the development and financing of these devices came from the government. In the USA, meanwhile, some of the developers were supported by commercial firms and others by the government and the academic establishment.

It is difficult in this sort of answer to set scales and criteria for similarity. I have shown earlier that these devices varied in techniques of operation, structure, shape, and size, and were intended for different unique applications. However, in retrospect, all these devices belong to the category described in the definition that I have adopted, of the automatic program-controlled digital calculating devices. How satisfactory is this answer, given that the various devices differ in every concrete regard, similar only in the abstract, and that the same background knowledge failed to accrue such results in many countries that also had it?

Answer 11

The automatic program-controlled digital calculating devices were developed during the period 1935-1945 in Germany, the USA and the UK because in the 1930s, conditions evolved for merging and incorporating components, tools and techniques which had been available previously, leading to the development of new tools with greater potential than each of the older components provided by itself.

This answer was given by myself. Its essence is that the whole is more than the sum of its parts; it is holistic, and it comes in response to Eckert's

> 'I have often wondered why somebody didn't invent the ENIAC 10 years earlier. The tubes were almost as good earlier... The switches were little clumsier looking and one thing and another, but it would have been possible to build a machine in 1933 that would have been almost as good as the ENIAC... Therefore, I have really to believe, at least for most of my experiences, that necessity is usually the mother of invention...' [7].

Aiken's development regards the synthesis of existing commercial calculating means into an automatic calculating device. Eckert's approach is a mild or moderate technological determinism as the sole explanation for technological development, reminiscent even of Marxist dogma, full of such expressions and wording of the likes of, 'forces were at work'. Forces are appealed to when causality remains obscure, much as syndromes are when a diagnosis is frustrated.

This does not provide explanation for those conditions required for the synthesis and integration of the various components, ideas and techniques into this type of device at the stipulated time and in those countries referred to, nor for any kind of event under any other circumstances. Also, the answer does not detail those techniques, ideas and components such that their synthesis and integration was needed to obtain this type of device, let alone if said techniques, ideas and components were found only in these three mentioned countries or anywhere else. This type of device needed digital calculating means, storage means for data and for instructions, such as punch paper tape or cards or an electric connecting switch-plug board, control means and input/output means such as pushbuttons, keys, punched cards, typewriters or teleprinters. As for the techniques implemented in these devices, it is known that they functioned on a digital representation, operating in a series of repeated sequences of cycles (iterations) by the difference method. Moreover, we know that the techniques and tools listed above were known and found in many other countries. Also, the levers, electro-magnets and vacuum tubes, or the idea of automatic technology, utilized in these devices were all abundant and common in many places around the world, yet in those places these automatic program-controlled digital calculating machines were not developed.

Nevertheless, there is some validity and empirical support for this answer. Indeed, in his proposal (1937), Aiken talks about integrating and synthesizing existing commercial equipment, like that of IBM, by means of developing an electrical control board, a very common instrument then, into an automatic sequential calculating machine for scientific needs. Compared to Aiken, other developers, Zuse (1936), Mauchly (1942), Louis Couffignal (1938), Atanasoff (1940) and Stibitz (1940), made the synthesis and integration of ideas and techniques to this type of device at a more primary, basic level, and in no specific roots in previous traditions of calculating means (as indicated in Answer 1). The synthesis and integration were expressed by the very profound and elementary use of techniques and technologies such as switches, communication, ideas from Boolean logic, felt intuitively, creating a totally new concept of a calculating device, not resting on any previously existing instrument or component.

The confusion that this answer displays derives also from the terminology used by the developers of these devices for the new components. This was partially based on terminology borrowed from the 'old calculating devices'. For example, prior to and even after the introduction of the automatic program-controlled digital calculating machines, the meaning of an 'automatic-calculating-device' was a device driven by means of a motor and not manually by a man. On the other hand, in the automatic program-controlled digital calculating machines, the meaning of 'automatic' is 'the execution of a complete and continuous sequence of calculating operations without any interference of a human computer'.

As aforesaid, the answer does not provide an explanation for the required conditions for the creation of that synthesis during the 1930s, whatever was unique in Germany, the USA and the UK, such that only there could these devices be developed and not elsewhere. Yet within the automatic program-controlled digital calculating machines were integrated sequential controls, telegraphs-teleprinters and telephone communications, calculating and storage based on Boolean logic, combined with the iterate differences calculating technique, each preexisting. This answer is easy to refute, because it is very simple to show, determinism notwithstanding, that different and diverse solutions do indeed derive from identical conditions and needs.

Answer 12

The automatic program-controlled digital calculating machines were developed during the period 1935-1945 in Germany, the USA and the UK because, for over 100 years, there had been parallel developments in a few domains of technology and mathematical logic.

This answer is provided by myself in order to provide background and prompt a critical analysis of the history of technology in Germany, the USA and the UK until 1935, towards an examination and comparison of the parallel developments of mathematical logic, the telegraph, the telephone, the radio, radar, and the electric power network that Edison was involved with in all three countries.

This answers, essentially, the first part of the question—why were the automatic program-controlled digital calculating machines developed in Germany, the USA and the UK—but not as to why at that time. And does it explain the abortive attempts made in other countries and their failure? France, Spain, the Netherlands and Austria all manifested parallel development of such domains. The Frenchman Louis Pierre Couffignal

(1938) proposed a scheme of an automatic, electro-magnetic, binary program-controlled device suitable for calculations in celestial mechanics. He succeeded in convincing one of the leading producers of calculating machines to manufacture this machine, however World War II cut this initiative off at its early stage. In Spain Leonardo Torres y Quevedo (1914) proposed a prototype of an electro-magnetic digital dedicated device with an extended logical capability, which would outperform anything then known of the devices designed at the end of the 1930s. Yet, Torres' prototype did not come to realization. In Holland, the Phillips firm made an abortive trial to construct a digital device, based on the control system of the telephone exchange. In Austria, at the turn of the century and during the 1920s, there was an attempt like that of Aiken's to combine IBM equipment under an imitation of an electric connecting board, such as that of a manual exchange. As for other countries, there is no evidence to indicate such a trend of constructing this type of device.

To reiterate, the answer does not provide the reasons as to the development of these devices in the period 1935-1945. And yet there was parallel development between Germany, the USA and the UK, for instance in the technological domains of electricity and electronics. As an immediate result of the Ørsted experiment (1819), the electro-magnet appeared almost in parallel in the UK and the USA, and subsequently, also in both countries, the phenomenon of induction (and self-induction) was discovered (1831). The electro-magnetic telegraph was developed almost simultaneously in these three countries during the period 1835-1845 in Germany by Gauss and Weber, in the UK by Wheatstone and Cooke, and in the USA by Morse, Vail and Henry. The French also claim priority in the development of the telegraph, apparently referring to semaphore, but no evidence supports this claim. The thermionic tube results from Edison's discovery of thermionics, for which he took the trouble to apply for a patent (1904). It was developed at once as a diode, in 1904, by the British physicist Ambrose Fleming, a scientific adviser to the Edison electric company, the forerunner of the General Electric Company of England. Lee de Forest improved the diode into a triode (1906) by adding to it an intermediate lattice. In Germany, Geiger (1908), induced by the thermionic tube's low pressurized gas principle, developed his famous elementary particle counter.

These three countries had also followed a parallel trend from the beginning of the 20th century in the domain of wireless communications and radar (including TV), up to its apex during the late 1930s. Similarly, the diffusion of the railway also brought the need to introduce new ideas and techniques of rapid track switching, signaling, timing and vocal and written communications. The penetration of these new technologies into the military was also in parallel in these countries: during the Civil War (1861-1865) in the USA, during the war against France (1870) in Germany, when Jean-Maurice-Émile Baudot, a signal officer, introduced the five signal binary fixed code on punched paper tape, while the UK had already utilized some of these tools during the Crimean War (1854). Edison embarked upon the electrification process in the USA, and he extended it to the UK and Germany by his daughter companies. The introduction of the railway system in the UK in the 1830s likewise spread very quickly to Germany and the USA during the second half of the 19th century, and to other countries such as Belgium and France, although there the process was much slower. It seems to me that one of the reasons for the introduction of radar was the mounting political tension that led to the outbreak of World War II, though such developments had begun already during the 1920s, in England as well as in Italy and Japan.

Until 1933, the University of Göttingen in Germany, under David Hilbert, was the world's center in the domains of mathematics and logic and half of its students came from the USA. The building of the Faculty of Mathematics in Göttingen was paid for with American funding. From 1933 onwards, Princeton University (New Jersey, USA) became the new world center for mathematics and logic. In parallel with the University of Cambridge in England, it formed an important core of mathematical logicians.

Answer 12 is controversial because parallel developments occurred also in France and other places but were cut short by the war. Many indications of parallel developments in Germany, the USA and the UK in a narrow sector of technologies and ideas for almost one hundred years, culminated during the 1930s in the automatic program-controlled digital calculating machines.

Answer 13

The automatic program-controlled digital calculating machines were developed during the period 1935-1945 in Germany, the USA and the UK because of a new conceptual tradition that emerged from a special type of strategic convergence that brought together several conceptual traditions of technologies and ideas that were complemented by economic, political and academic interests.

This is my own extensive elaboration on the view of T. M. Smith (1970), who was the first to level serious doubt towards the linear approach of writing the history of computing. He suggests that the modem computer resulted from the convergence of several technical and computing traditions that had become interrelated and influenced one another for hundreds of years. He claims that influences of these traditions had reached their prime with the development, during World War II, of the mathematical calculating means, and that they then brought about the construction of large scale (in its twofold meaning) analog and digital calculating devices.

Were then the modern computer devices in any way derived from earlier traditions, or has their appearance nothing to do with past traditions and activities? The truth seems to be somewhere in between these two options.

The contrast between Answer 13 and Answer 1 is this: in Answer 1, the argument rests on a linear sequence in which the development of calculating devices belong to a single tradition; in Answer 13, in which Smith's claim is examined, several lengthy traditions of technical developments are involved, including that of measuring devices. But in the present study, such connections stand refuted as unnecessary; the introduction of these devices in the period 1935-1945 did not derive from the traditions indicated and related by Smith. Moreover, the label of 'computer pioneers' or 'fathers' that the literature applies to the people involved is also shattered here as quite inadequate and misleading, and even more decisively so.

Answer 13 is controversial, because it has no reference to the parallel development of these devices, exactly so in these three particular countries. The explanation of that convergence and synthesis of several traditions of technology and ideas to a new tradition during World War II is somewhat vague. The meaning of 'strategic interests' bringing about support from the economic, political and academic establishment is also not sufficiently explicit, in that other countries like France and Italy may also have found strategic interests, yet these devices did not appear there. We know distinctly that the political regime in Germany, during the late 1930s, was entirely different from that in the USA or in the UK, a matter which also affected the economy and the academic institutions (see above with regard to the decline of mathematics and logic at Göttingen).

Nevertheless, Answer 13 does shed new light on the evolving new tradition from which these sort of devices could then derive. I have shown that binary technology was dominant in these devices and that Boolean logic and certain calculating techniques were incorporated in them, even unconsciously and intuitively. The electro-magnetic tradition, as we already know, began during the 19th century, when it was first utilized in handwritten wire-line communication before it transitioned gradually into voice communications and then into facsimile or image transmission as well as into electrical switching in control, punch and tabulating equipment. The binary logic tradition (Boolean logic) is also a 19th century 'product', and was utilized unconsciously in the design of electrical circuits such as the telephone exchange board, and in punch and tabulating equipment. Only by 1936 was Boolean logic implemented intentionally, in the insurance industry by actuaries [8]. This derives, incidentally, from the subtitle of George Boole's 1854 *An Invention of Laws of Thought which are Founded on the Mathematical Theories of Logic and Probabilities*. The intentional application of Boolean logic for engineering calculations began only after Claude Shannon fashioned the direct transition from Boolean logic to electric logical circuits with switches (1938). Until then the construction of switching circuits was intuitive and considered an art. Normally, this is the approach to a domain that had not been accepted as a scientific discipline (see Professor Joseph Agassi's writings on technology on this issue).

The discreet technology of electrical pulses deriving from thermionic tubes (1904), adopted between 1910-1940 in the radio, wireless, radar, television and telephone automatic exchanges, began to enter into electric logic circuit technology by 1919. The Eccles-Jordan trigger (1919), a circuit aimed at preserving two distinct complementary states by utilizing three thermionic tubes, known today as flip-flop, enabled the storage of a single bit of binary information. Hitherto in the 1930s, this type of trigger was implemented using rapid counters, such as those of Wynn-Williams (1931). At the end of the 1930s, the thermionic tube served as a very important component in various computing units.

A variety of technologies and abstract ideas based on distinct states, conceptually interrelated, stood at the disposal of the developers, enabling the synthesis with other calculating traditions of differences and iterations, thereby enabling higher precision calculations than were then known and had hitherto been unreachable. To what extent were the economic, political and academic interests involved in the development of the automatic program-controlled digital calculating machines?

As for the financial support provided to the developers, history records that Zuse developed the Z1 and Z2 from resources and means he composed himself and that he built almost personally, only getting some minor financial assistance from a calculating machines producer. Only the Z3 (1941) was financed by an aircraft firm. Zuse was compelled to establish his own firm in order to produce his two special-purpose models. Mauchly and Eckert were supported and sponsored by the US Army and the

University of Pennsylvania, under whose supervision ENIAC was constructed. Atanasoff received upkeep from Iowa College and a modest grant from Iowa State. Aiken was supported from the outset by Harvard University and IBM; they provided manpower and other resources to the project. Later, Aiken and IBM parted ways. By contrast, the Bletchley Park engines were developed with Premiere Churchill's personal support and intervention. He allocated to them top priority, the best manpower and resources in the most advanced domains of the era, of electronics and radar. This priority enabled them to skip an entire technological generation in computing within nine months. It is in the UK, it seems, that the greatest number of these devices were produced: some sixty electro-magnetic devices (Bombs), and between twelve and fourteen electronic Colossuses of several versions were completed before the War ended. There are indications that many Bombs and machines similar to the Colossus were also constructed in the USA.

The Bell Company was the only commercial firm to intentionally enter the development of these devices due to economic considerations and on its own initiative. NCR did so marginally, as it supported the Rapid Arithmetical Machine project at MIT between 1938 and 1942. Nevertheless, by 1939, Bell was practically the sole pioneer in the industry of automatic program-controlled digital calculating machines in the USA. The sympathy of the academic establishment resulted from the uniqueness of these devices and the prestige involved by obtaining or having built them, much as with the cyclotron.

It is well known that the devices of Zuse, Bletchley Park, Bell and Aiken were immediately brought into service for the war effort. The aircraft industry utilized Zuse's Z3 and the two special S1 and S2 machines. The devices of Bletchley Park were developed for the war effort to get military strategic intelligence in real time. The Bell Models II and III were developed for military equipment testing and for the training of anti-aircraft gunners. The Harvard Mark I was applied for calculating firing range tables for the Navy. ENIAC at the University of Pennsylvania was developed solely for needs resulting from the war, the need for artillery firing tables for newly developed artillery, though it came into active service only after the War.

How much the shadow of War influenced the development of these devices is hard to tell. Schreyer, in a letter from 15th October 1939, asks for Zuse to be released from the army. In the letter he wrote,

> 'The machine is primarily for technical calculations… Since the calculations are done very quickly the machine is a useful aid for desk calculations which are required in laboratories. It can also be a valuable aid for setting up tables used by the artillery and warships. It can be used as a valuable aid in the calculation of weather charts... We are here concerned then with a computing machine which can be of valuable assistance both in the production of military equipment as well as in its applications.' [9].

Sufficient evidence indicates that the ideas that led to the development of these devices were conceived prior to War and even to the events or atmosphere connected to the War. In some of the examples, the War gave impetus to the development of such machines and created a favorable atmosphere for those responsible to make the decisions to support such projects. In other cases, however, history shows that the War had no influence at all while in other cases it caused their postponement or termination.

To reiterate, this answer remains controversial.

Summary on the Main Issues under Debate

What led to the multiple, simultaneous appearance of automatic program-controlled digital calculating machines in Germany, the USA and the UK during 1935-1945? Considerations the alternative answers to this question indicate that none of the answers are definite or conclusive. Most of them were refuted.

Answer 1, in spite of being the most popular and the commonly accepted, is nevertheless false: these devices were developed in detachment from previous traditions of calculating means. Before 1935, the wheel was the exclusive means of automated calculations until the advent of the two stage switch, integrated in logic circuits with no awareness of Boolean logic, in order to serve as the main means for calculations and the storage of results.

Answer 2 is false: fate, luck, destiny or chance just do not fit real events.

Answer 3 is false: automation, management and the assembly line had no influence whatsoever on the development of the devices in question.

Answer 4 is false: the devices in question were developed not in response to any need for more precise testing and simulating means for industry and for scientific research. The current technology was then entirely adequate. It was only after these devices had been developed that they were adopted for defined aims of control, measurement and simulation.

Answer 5 rejects the mythical link concocted by the computer science community between the mathematical logicians of the mid-1930s, particularly Turing and his 1936 paper on the universal machine, and the digital computer. All this is contrary to history. The influence of mathematical logic dominated the devices subsequently known as 'computers' only after 1945. This answer is a travesty; it does not deserve serious consideration.

Answer 6, the claim that the devices in question were developed at the time because of the need for faster and more accurate calculations in engineering and sciences such as physics and mathematics, is at best partial, suitable only for Aiken's case. Not one of these devices developed during the period 1935-1945 was designed in advance to deal with problems of quantum or nuclear-atomic physics.

Answer 7 is supportable, in that some of the developers did indeed demonstrate discontent with the previously existing calculating devices. But further evidence refutes it, since other developers were not influenced by the limitations found in the previously existing conventional calculating means and so it did not present them with any incentive.

Answer 8 rests on the supposition that under identical conditions, identical interests are created and lead to identical results. Yet it is easy to show that in other countries an identical body of knowledge also prevailed, yet with different result.

Answer 9 too has to be rejected. The reasons for rejecting it are the opposite of those for rejecting Answer 8. It explains nothing, neither the nature of the problems from that allegedly led to the construction of the calculating devices in question.

Answer 10 bridges the difficulties raised by Answers 7 and 8. It is inconsistent: there is truth in its claims that the devices in question were different and diverse and that they originated from different problems that engaged the various developers; still, all of them meet the criteria of the definition of the automatic program-controlled digital calculating machines. This, on the face of it, exposes this answer as absurd.

Answer 11 is rejected on evidence that the tools, ideas and techniques required for the construction of such devices existed in other countries, but nevertheless the devices in question were not developed there. Besides Aiken's example, which is exceptional in many ways, the developers did not adopt existing tools related to calculations; instead, they utilized binary technologies (as described in Answer 1) with techniques of logic-circuits cyclic computations by the method of differences. At best, then, this answer remains controversial.

Answer 12 remains open to dispute. It is partly refuted because practical and theoretical developments of similar devices occurred in other places. And yet, in some very restricted domains of technology and mathematical logic, a unique parallelism occurred in the developments only in the three named countries.

Answer 13 initially struck me as the closest to the truth. But I came to realize that it does not provide an explanation for the simultaneous discovery of these devices at that time and in those places. 'Strategic convergence', the transition from several long-standing traditions into one new tradition, is a most ill-defined process. How exactly does such a process occur, and how, does a new invention—the computer—evolve out of that new tradition? It amuses and amazes me to notice how sometimes serious people think that by finding or ascribing a new term for something, they provide a solution to a given problem. They are duped by their own linguistic sleight of hand! Evidence indicates very clearly that during the 1930s different political conditions and regimes existed in the USA, the UK and Germany and that these influenced their economies and their academic establishments in vastly different manners.

Finally, I have shown that there is at best only poor empirical support to any attempt to relate the development of these devices exclusively to World War II, or to the tensions leading to it. Some devices served the preparations for the War but the War stopped or postponed other developments, probably many more of them.

CHAPTER SIX

WHAT CAME OUT OF ALL THAT?

Introduction

The discussion of this chapter turns upon this question. What came out of it all and how did awareness or knowledge dawn upon the developers, if it did at all, that they were engaged in the same pursuit? This chapter is thus a digression from the central problem of why, exactly, in the period 1935-1945, automatic program-controlled digital calculating machines developed simultaneously and in parallel in Germany, the USA and UK. Therefore, this chapter will be shorter and more compacted than the previous ones, even though it is tempting to follow up to the present day and the evolution of the present state of the information revolution, such as personal computers, modems, the Internet, the information superhighway, etc. And though I have given seminars and written on these subjects, nevertheless I will refrain from entering them here or extending the book beyond its original scope and aim. These topics deserve separate studies; I hope to write one.

(Even in presenting events after 1945, I continue to refrain from the use of the term 'computer' for these devices. I explain this in Appendix A, 'The Development of the Term and Notion of Computer'.)

The era after 1945 begins with the publication of the 'First Draft' (June 30, 1945) and the 'Trinity Paper' (first edition July 28, 1946, second edition September 2, 1946) [1]. These publications mark the turning point in the construction of automatic program-controlled digital calculating machines. From then on, the basic features of these devices and their principles were in the public domain.

The period after 1945 is also less controversial in the literature with one exception, a curious phenomenon that I elaborate on in Appendix B, 'The Borrowed Fame'. This calls for a brief summary. Here it is. For the first time a program was openly announced, with detailed specifications and requirements, for the construction of an automatic program-controlled digital calculating machine, and in close cooperation between the USA and the UK during the War in the development of decoding devices. That cooperation continued after the War in the development of automatic program-controlled digital calculating machines.

I did not find any interest in discussing the present or predicting the future, though for so many the temptation seems irresistible. This is a sort of engagement that can easily, even if unintentionally, turn any discourse to preaching at worst and admonition at best, which are both undesirable in historical analysis. Hence, I have decided to cut short the discourse on events after 1945 somewhere at the end of the 1950s and the early 1960s, when the final patterns and logical concepts of these devices were already crystallized. In the period after 1960, the uniqueness of these devices is not merely limited to the domain of experts in the field, but is also absorbed by the general public. The introduction of a new discipline, termed 'Computer Science', in the early 1960s can serve as the terminus for this discourse. Yet, even today, there remains difficulty and controversy in defining what exactly is meant by the very term 'computer science'.

For convenience, this era is divided into two periods: the period between 1946 and 1952 and the period afterwards. The period between 1946 and 1952 terminates with the appearance of commercial computers and the establishment of institutes intended to advance their study and application, meaning a period when computers were manufactured for the free market by commercial firms, some of which were launched to perform such a task. The period after 1952 is characterized by the takeover by commercial firms, manufacturers of calculating equipment and electronics, of the newly-established independent firms of the period 1946-1952. In that period, academic institutions lose their leading role as developers of such calculating devices in favor of other enterprises, and instead shift their focus to the training of academic manpower and the development of efficient techniques and procedures for the use of calculating devices.

Periods in the History of Computing

The division and classification of historical events as reflected here deviate from the traditional divisions common in the literature and research of the history of computing as is commonly accepted in reference and in context to the events. This is so due to my effort to understand the causes that brought about the simultaneous and parallel development of these specific calculating devices in the period 1935-1945 in Germany, the USA and the UK. The period until 1935 served as a historical background for refuting the commonly received view of the history of computing as linear and continuous, as Goldstine (1972) for example has presented it. He also maintained the division of this history to three periods; he claimed that this is a natural division. (As far as I know, the concept of a tripartite division is most accepted by certain army and military figures.) The first is up until World War II, which serves as a historical background; the second concerns developments that took place during the War; and the third treats all that occurred afterwards. Goldstine focuses, naturally, upon ENIAC, that being the axis around which he embroidered his history of the computer. In fairness to Goldstine, it should be noted that his book was probably intended to describe and to commemorate the development of ENIAC by emphasizing the role of von Neumann in its construction. Goldstine makes no pretension of writing a comprehensive research of the history of the computer. He also preferred to concentrate on ideas that, according to the common view, led to the development of computers. Other scholars prefer to focus upon the portion of the history of computers according to the introduction of new components, breakthroughs in new technologies and technical means. So, for instance, Ceruzzi (1980) focuses on the prehistory of the computer which, in his view, is the period between 1935 and 1945. Alt (1972) views the years 1937-1947 as the archeological era of the computer. In contrast to Ceruzzi and Alt, Eckert (1978) has rejected all pronouncements made to in order indicate a breakthrough of a unique way, and distinguished four milestones in the history of the computer prior to 1966, in which significant changes took place. Eckert's classification is as follows.

> 'So I setup my own markers, which were based more upon choosing a time period of significant change rather than the announcement of some particular breakthrough. I chose the early period to be from 1943-1950 [termed later on by him as the Early Era]. In that seven-year period we used existing components largely, but there were new system ideas as well. We did not understand the user's requirements very well at that time. The second period [termed the Growing Era] was a longer one—from 1951-1960. I called it the growing period. I felt that even though there were more developments and breakthroughs in this period, fundamental progress was really slowing down. New components came out—transistors, diode gates, tape units, mass storage, character recognition devices.. Programming systems become important. Software became important. I include software developments in my list of breakthroughs in the same way as I would include hardware developments. I find no distinction between them.
>
> 'The third era I called the refining era. And that dated from 1961 to 1975. Bear in mind that I made this observation in 1966.... Now I forecasted that in this period we would mostly see refinements of ideas already started earlier, especially in speed and storage of all kinds. We would see very few

> really new systems ideas—a few in communication and real time and timesharing, but the basic input/output problems would still remain.... The fourth era I said would a maturing period starting in 1975. And I said that of this period I felt things would become more static unless we get some kind of breakthrough in recognition (especially voice and pattern recognition). We need a breakthrough in self-learning on some kind of grand scale so that the software problem doesn't remain so all-encompassing.' [2].

The last reference to the division of that brief history to periods is found in the Israeli Open University *Introduction to Programming and Knowing the Computer* (1979); Unit 12 has a section entitled 'And this is the history of the computer for its generations' [3]. That reference is not original, and is not limited to the Israeli Open University; it appears in most computer science books, and therefore I will present it here in full:

> The Zero Generation—1944-1950. This generation is characterized by the fact that computers were not produced on a production line. Each computer was a unique product. The basic components were electro-magnets or vacuum tubes and their programming capability was very limited and particularly complex.
> The First Generation—1951-1957. This is the first generation of commercial computers. Here the technology of the components is based on vacuum tubes and feature a richer programming language of up to one hundred instructions.
> The Second Generation—1958-1964. This is the generation of transistor computers and the introduction of Higher Level Languages such as FORTRAN.
> The Fourth Generation—1972-1978. The present generation [he book is from 1979], characterized by the very high compression and miniaturization of electrical circuits onto an electronic chip, the introduction of the microprocessor and of more advanced programming languages.

As is common in descriptions in such books, this one glides into futuristic predictions or preaching as to the advantages or dangers of the computer. I have included and surveyed those partitions of the history of computer, but intentionally without taking any stand or making any criticism. Any of those partitions expresses a view as to the history of computer, consciously or not. As I have referred to the various approaches to the history of computers in many places here, let that suffice. I now return to the main issue of this chapter, the outcome of the previous years and the questions at hand: what came out of it all? How has such uniformity arisen, internationally and in isolation? And when did an awareness or knowledge arise that the developers were engaged in the same pursuit of the automatic program-controlled digital calculating machine technology?

The period 1946-1952

The most impressive and important phenomenon that occurred immediately after the end of the War was the enormous growth of the community occupied with the research, instruction, learning, design, construction and use of the automatic program-controlled digital calculating machines. If until 1945, to my estimate, there were about fifty people involved in this discipline in the entire world, then, in 1947, to my estimate, this community had already expanded to some eight hundred people.

Between July and August 1946, a seminar was held at the Moore School, the first of its kind in the world, on automatic program-controlled digital calculating machines, catering for a selected group of twenty-eight scholars from the USA and the UK [4]. That seminar held discussions of both the logic-mathematical aspects of the development of these calculating devices and their technical, engineering aspects. A new title, 'large-scale', meaning the emphasis of the outstanding property of calculating power exhibited by these devices, was now routinely attached to these devices. This was to distinguish them from other calculating devices, including those that performed huge amounts of complex calculating tasks, not because of their sheer bulk, though this was also an extensive historical detail of which many scholars are unaware [5].

Later, both in the UK and in the USA, many conferences on 'Large-Scale Calculating Machinery' were arranged, with hundreds of participants. The first such conference/symposium was held at MIT in October 1945 to inaugurate the electrical differential analyzer known as the 'Rockefeller Analyzer', an analog device completed by 1942 with limited programming capability, declassified only after the War. That conference was sponsored by the editors of the magazine *Mathematical Tables and other Aids to Computation* (MTAC) and organized by a joint committee of Americans and Britons. It was still a closed conference and participation was limited by invitation. It had eighty-four participants from government, academia and corporations [6]. Even before the War, calculating devices served as the subject-matter of conferences, lectures and training sessions were held on, but these gatherings were not a part of a distinct and unique discipline. For instance, the Gibbs lectures (1936), where Bush lectured on 'Instrumental Analysis' (1936), was within the framework of the American Mathematical Society. The special course, 'The theory and design of calculating devices', planned for 1939 at the Moore School, was canceled due to a lack of participants (Mauchly was supposed to attend). Of course, at various celebrations for the three hundredth anniversary of the invention of Napier's logarithms (1914), various calculating devices were discussed. Even earlier, in 1912, an exhibition of calculating devices was held during the fifth international congress of mathematics in Cambridge. The catalog from that exhibition produced by J. W. Whipple says that at that time there was on the market no multiplying device able to carry out automatically an extensive series of multiplications.

The difference between those conferences held before World War II and those held after it is not just in the type of devices under discussion, but also in the demonstration of new techniques, concepts and principles in the design of calculating devices. Discussions were held already before the end of the War on the character of calculating means and properties of particularly high speed components for calculating needs. In the USA, such meetings were held in the framework of the National Defense Research Committee (NDRC) by the mathematical panel, section 2 (in charge of the development of fire control devices) and section 3 of the committee (in charge of developing calculating devices). Most of the experts in the *milieu* of calculating components and calculating means participated in these meetings, among them Aiken, Stibitz, MIT and RCA members and others. The committee also tended to consult with many outside experts and their organizations. However, its decisions were very much influenced and dominated by Aiken and Stibitz. Similar and *ad hoc* forums existed in Germany and the UK, which I have mentioned in previous chapters (NPL in the UK, and IPM in Germany).

After the end of the war, the Allies encountered the experience and the know-how gained in Germany in the domain of digital and analog calculating devices. Zuse and his colleagues were interrogated about their work. The records of these interrogations appear in the *FIAT Review of German Science 1939-1946* (1948) [7]. On these occasions the similarity between Zuse's devices and those developed by Aiken and Stibitz was discovered for the first time [8]. The case of Helmut Höltzer (or Hoeltzer), the developer of the electronic analog differential analyzer, is interesting. At the beginning of 1942 he and his team built an analog computer to calculate and simulate V-2 rocket trajectories. After the War he had his oral PhD examination in the presence of an American intelligence officer as an observer to prevent any leakage of classified information. He was flown almost immediately afterwards (in May 1946), directly to Fort Bliss, Texas, to participate in a rocket project under Wernher von Braun. Later on, Höltzer's developments were incorporated in flight control-systems in aerospace projects including the moon landings. [9]

The first Harvard Symposium took place between 7 and 10 January 1947. It was organized by Harvard University and the US Naval Office to inaugurate Mark II. Three hundred and thirty-six people participated (out of seven hundred respondents who expressed the wish to participate). Babbage's grandson Richard gave the opening address on 'The Work of Charles Babbage'. Thirty-four new papers were given in that symposium. The program included the exhibition of Mark I and Mark II. Mark II was moved after the symposium to the Navy's proving ground at Dahlgren VA. During the symposium, the characteristics of ENIAC were also disclosed to participants [10].

On October 24, 1947, the American Computing Machinery Association (ACM) was established, based on the East Coast Association that had been founded several months earlier. By January 24, 1948, this organization alone (ACM) numbered three hundred and fifty members [11].

In May 1947, the institute for Numerical Analysis was established on the West Coast at the University of California, Los Angeles, by the American Federal Bureau of Standards. Its declared aim was this.

> 'The central function of the institute is to perform mathematical research related to the efficient use of Automatic Digital Computing Machinery.'

Even here, from the statement of the aim of this institute, we may gain some notion as to the classification by which these devices were evaluated: Automatic Digital Computing Machinery. Or, as R. W. Hamming entitled his paper in Metropolis (1980), 'We Would Know What They Thought When They Did It'. Clearly, there was as yet no concept of the 'computer' in the modem sense. However, they felt that this 'machinery' was something terrific.

At the Institute for Numerical Analysis, a symposium was held between June 29 and 31, 1948, on 'Modern Calculating Machinery and Numerical Methods'. Here, the number of participants was already five hundred and fifteen [12].

The second Harvard symposium on 'Large Scale Digital Calculating Machinery' took place on September 13 to 16, 1949, to mark the inauguration of Aiken's Mark III with Lehmer speaking on 'Mathematical Models in Large-scale Computing Units'. The number of participants there exceeded three hundred.

Similar conferences and meetings were also held in the UK. However, when first taking roots as an independent discipline there, these devices were classified by the community of their users under the term of 'High Speed', presumably borrowed from metallurgy in the steel industry, in which the term 'High Speed Steel' denoted new alloys of steel for faster cutting or chipping machinery tools. So, for instance, a special meeting was held with the name 'A discussion on computing machines', under the aegis of the Royal Society on March 4, 1948. In the opening address Professor M. H. A. Newman indicated that the discussion

> 'would be confined to machines which are "automatic", i.e., require no human intervention at any stage; "digital", i.e., such that separate digits of each number are stored in the machine at every stage (in contrast to "analog" machines such as the Differential Analyzer where the numbers are reproduced by directly measured physical quantities, e.g., lengths); and "general purpose" machines, i.e., machines able without modifications to carry out any of a wide variety of computing jobs' [14].

Nevertheless, Newman's own lecture focused on 'A historical survey of digital computing machines'. Additional conferences attended by many participants were held in Cambridge between June 22 and 25, 1949, dedicated to the inauguration of the EDSAC [15].

A pamphlet, possibly the first of its kind, appeared in May 1948 for the US Office of Naval Research, with a glossary of terms used for discussing such devices. The pamphlet is twelve-pages long. It was apparently prepared for the Whirlwind computer project that started at MIT in 1944. The preface to this pamphlet is particularly intriguing:

> 'The reporter of a new art is always confronted with the problem of describing previously unknown concepts and devices for which there are no words in the general vocabulary. Project Whirlwind reports inevitability contain a considerable number of specialized terms used in new senses.' [13].

The extent of the public's absorption of the concept of automatic calculations is evidenced by the many lectures Aiken was invited to give on these calculating devices as well as at very respectable events such as the fourth conference for young talented scientists on March 3, 1945, and the UNESCO conference held in Paris on November 14, 1946.

At these meetings on these calculating devices, the principal lecturers were usually people who had participated in person in such projects as have been discussed here. Even Atanasoff was invited to the first Harvard symposium and Aiken gave a lecture on storage means, although he did not otherwise participate, I do not know why [16].

The media in general, and the print media in particular, including scientific and popular magazines, released many publications on the automatic program-controlled digital calculating machines developed in the USA, the in UK and in Germany. I will add a few words as to the attitudes and the contents of those publications related to these devices. At the end of the 1940s, many perceived the uniqueness and the broad untapped and unsuspected potential of these devices, and the challenges that they presented to society, to science and, in particular, to mathematics. This perception was shared not only by the communities involved in the domain and their development, but the general public as well. Titles like 'Big Brains', 'Automatic Brains', or 'Electronic Brains' were very common for media presentations. The expectations were exaggerated, inviting reactions towards the preposterous belief in the capabilities of these devices. There was already awareness that society was on the verge of a new large industry and such questions were raised as, 'are such machines able to think?' [17]. The Harvard Computing Laboratory published a pamphlet on 4th August 1949, edited by J. R. Reynolds (then the deputy president of Harvard) and found in Aiken's papers in Harvard, entitled *Revolution in Science and Industry: The Work and Promise of the Automatic Digital Computing Machine of Harvard Computation Lab.* It opens by stating that today everything has changed because of the machine of Harvard, a 'High Speed general purpose "Automatic Digital Computing Machine" ... The machine holds great and immediate promise for breaking the dam in mathematics. Calculations which had retarded scientific and industrial progress in men's history.'

This propagandistic hyperbole of the pamphlet was hardly unique to Aiken or his colleagues at Harvard. Every academic institution was aware that its prestige was at stake if such a device was not to be found within its premises. The notion that these devices set the people of the era before a second industrial revolution is well attested, for instance in publications such as that of L. N. Ridenour, then a professor at University of Illinois, in *Fortune* in May 1949:

> 'The automatic digital computer is currently the highest expression of mechanization of mental function. As such, it is the most profoundly significant symbol of the second industrial revolution, which is on the way.'

He says there that the first industrial revolution liberated us from physical toil, while the second revolution would free us

> '... from unproductive, repetitive and time consuming labor by providing him with mechanical aids to save him mental effort.'

Typical to the period 1946-1952 were heated debate and disagreement as to the preferred technology to be adopted in these devices: electro-magnetic technology or electronic technology. In the USA this controversy was resolved only by 1949, when Aiken finally decided to develop Mark IV as a completely electronic device. In the UK, the development of such relay-electro-magnetic calculating devices proceeded until the early 1950s. Nevertheless, at the national level, this controversy, if it existed at all, was resolved much earlier, once and for all, with the construction of the Colossus in 1943. It results, therefore, that the outcomes of Bletchley Park served as the leading factor in the development of these sorts of calculating devices in the UK. The scientific establishment, including the Royal Society, the relevant government agencies, and the military authorities, all supported and encouraged the development of such devices.

In this period, governments were very generous in providing resources for such developments. Many academic institutions began to accept financial support from government and military sources, often through such *ad hoc* bodies such as the NDRC, where people with diverse interests, like Aiken, Stibitz and von Neumann, enjoyed great influence. It was not always essential matters that guided these sources; naturally, vested interests and prestige were involved also in decisions that concerned the designs of Mauchly and Eckert.

This period is also characterizable by ever growing and closer cooperation between the USA and the UK in the development of such devices and related technologies. There were exchanges of scholars; for instance, Harry Huskey joined the Automatic Computing Engine (ACE) project of the National Physical Laboratory (NPL) in 1947 and worked closely with Turing. At the Princeton Institute for Advanced Studies (IAS), von Neumann and Goldstine conducted a very liberal policy for the diffusion and dissemination of know-how linked with the design and construction of such devices. The Institute enabled many scholars from the USA and all over the world to come to study the subject and improve their skills. At times the Institute even financed their expenses. Though I have referred to its limitations in preceding pages, this generous policy of the IAS later proved most rewarding, as most of its participants followed von Neumann's trend in the design of computers. However, unconsciously, they also absorbed and transmitted the biased legend of von Neumann's contribution to the initial history of the computer or the development of the automatic program-controlled digital calculating machines.

In Germany, after its defeat in the War and its unconditional surrender, a complete stagnation ensued in the development of these devices. Zuse, who started the construction of Z4 in 1942 as a multi-purpose device, was bound to move it at the beginning of 1944 from Berlin to Göttingen because of the constant air raids on Berlin. It performed important calculations for experiments at the Institute for Technical Physics at the University of Göttingen. The Z4 was moved once more to Hinterstein and Hopferau in the Bavarian Alps (the Harz Mountains). There it was hidden in a cellar until its transfer to the Federal Polytechnic Institute in Zurich, Switzerland, in 1950. During the period 1945-1950, Zuse focused on problems concerned with programming languages—the *Plankalkül* (Plan Calculus). The person who acquired the Z4 from Zuse was also one of the first to tackle the problem of programming languages, in particular high level language. It is considered as one of the first attempts to design a formal language for programming. After installing the Z4 in Zurich, Zuse established his own firm that, at the outset, only produced electro-magnetic automatic program-controlled digital calculating machines. The first such device after the War was the Z5 (1950); it was built for *Ernst Leitz GmbH*, the optical corporation. Zuse built his last electro-magnetic device, the Z11, the mid-1950s. In the late 1950s he moved into the manufacturing of electronic devices—of computers.

A few words on the development of programming languages. Every computer has a specific set of instructions that it can execute once an instruction is placed into the appropriate part of the machine. The set of symbols that the hardware can interpret for this execution is the direct machine language. Most of the devices were designed so that their storage locations and registers contained binary characters (bits, binary digits); the most common machine language was binary. This form was very complex and that is why, at the time (1945-1952), computer programmers were on the level of Turing and von Neumann. A partial step to alleviate this difficulty involved the use of nmemonic codes to represent the instruction, while the rest of the information was left in binary form. While this was a partial improvement, it was still far from easy to write even one instruction correctly. The next step forward came when numbers representing the storage locations or registers in the computer were allowed to be written in decimal form. Now, the borderline between machine language and symbolic language was not well-defined. While this was an obvious improvement, it was the development of completely symbolic notation and addressing for both instructions and data that freed the programmer from worrying about changing all occurrences of any given sequence of instructions. A preliminary step in this direction was the work done in 1952 at MIT on

Whirlwind and on Rochester, that used the numeric 'symbolic addresses'. These numbers had no nmemonic or numerical significance but were merely used as symbols for addresses. The culmination of this early work was the use of mnemonic symbols for both instructions and data. Virtually all the significant difficulties that appeared in those days were overcome by the increasing development of higher level languages. This was not the case until circa 1959, with the development of new operating systems. One of the first meetings to discuss the subject that was then called 'automatic programming' was sponsored by the Office of Naval Research in May 1954. The next meeting was a symposium on 'Advanced Programming Methods for Digital Computers', held in June 1956 under the joint sponsorship of the Navy Mathematical Computing Advisory Panel and the Office of Naval Research. The next meeting of major importance was the symposium on 'Automatic Coding' held in January 1957 at the Franklin Institute in Philadelphia. For a detailed account on the development of programming languages, see Jean Sammet, *Programming Languages: History and Fundamentals* (1969).

The USA was then the leading nation in the domain of such devices. At the end of the 1940s, many manufacturers of these devices sprung up in the USA. Among the other founders was a group who had retired from the Navy, specializing in the development of decoding methods. The openness of the academic and military establishments with friendly financial atmospheres contributed to the acceleration of the development of such devices. The US Navy was interested then in keeping this group of professional retirees together. The Navy supported that group in any possible way; it even offered them a secret electronic computer for decoding ciphers [18].

The estrangement between the members of ENIAC team at the Moore School produced two new focal centers in the design and construction of calculating devices. For a detailed account, see Appendix B, 'The Borrowed Fame'. One center is the IAS at Princeton, headed by von Neumann and Goldstine, officially established on February 17, 1946. The other center is the Eckert-Mauchly Company, established after their retirement from the Moore School on March 31, 1943. The Moore School then consequently lost its lead in the development of this type of device.

An additional center worth mentioning is MIT. In the late 1940s it gradually became an important factor in the design and development of devices and of their components. These came to be known as 'real-time' computers.

The story of the various developments that occurred in those places and that were copied in other places go beyond the scope of the present study. Suffice it to say briefly that both in the USA and in the UK, the original developers of these devices were greatly influenced by what happened during the period of 1945 onwards.

After the declassification and the dissemination and diffusion of these devices to the public, especially to the scientific and professional community, the developers were for the first time able to produce a communal vision as to the deeds of their colleagues, making explicit that from their vantage point of view the different devices were identical and that difference between their various implementations is in technology applied to design and to components. In 1946 it was also clear to all concerned that the binary numerical base notation provided a distinct and definitive technological advantage over any other notation. Regardless of the difference in notation, there is no difference in the programs that can run on any of these devices. It also became clear that the great advantage provided by electronic technology in increasing speed comes with the disadvantage of its technical unreliability. Conversely, the advantage of the electro-magnetic and electro-mechanic devices is their high technical reliability and minimal need for maintenance, but their main limitation is their low calculation speed.

From the moment that these devices were accessible to the public, with the exception of the British Colossus that was not officially disclosed for decades, it was made clear to all concerned that in various places that they were developing devices on identical principles; however, each specific implementation of the general principles was designed and suited for a specific purpose. All of them claimed that they were aware that they were dealing with a general-purpose device, even though they did not mention it or specify it directly or explicitly in their proposals (the term they would have used is ‘multi-purpose,’ because ‘general-purpose’ meant a universal machine in Turing’s sense).

Still, one point remained in dispute among these developers. It was the extent to which they were aware, before 1945, of the idea of the internal storage of instructions (see Appendix B, ‘The Borrowed Fame’). Most developers claim that the concept of internal storage was obvious and did not require any specific reference. This, in a case, is a deterministic claim with the result that anyone who turns to the design of an automatic program-controlled digital calculating machine is bound to reach the principle of internal storage. This deterministic claim and the historical evidence are in conflict or are at least seemingly in conflict. Admittedly, there is some truth in the claims of von Neumann's supporters (Goldstine *et al.*) that the explicit formal expression of the idea of internal storage was a vital pre-condition for its successful construction. Yet, the opposite is also admittedly the case: people may apply an idea or a technique, and, to repeat, with the use of the explicit formal expression of the idea of it, yet without being aware of it. (Writing prose without the knowledge that one is writing prose, to use the example of Molière; using formulas of Boolean algebra with no notice of this fact—even despite familiarity with Boolean algebra. Playwright and philosopher Jean-Paul Sartre made much this fact a central item in his works.) The 'First Draft', followed by the 'Trinity Paper', paved the way to the conscious application of internal storage. Most of the devices designed after the date of these two reports already included the idea of internal storage. It is intriguing that one of the first applications of internal storage was made by IBM in 1948.

Since in the UK and the USA in that period most of the budgets for this type of device came from government agencies, the 'Trinity Paper' had crucial influence, in particular in the USA, on the design of the future generations of devices of this type. For, in these two reports the potential customers had seen a contract pattern from which they were not allowed to deviate. In the UK, by contrast, two leading doctrines had existed after 1946. One doctrine was Turing's. It advocated minimum use of hardware. The other doctrine was the opposite. It became the governing view in the USA; it was that the design of computers should follow the architectural concepts of von Neumann as presented in the two reports, the 'First Draft' and the 'Trinity Paper'. Hence, also my label for this last report. The word 'Trinity' represents two aspects of this report. For one thing, it alludes to this report having been written by three individuals. The second aspect emphasizes its binding strength, which is so powerful in the design of calculating devices, like religious dogma or the Holy Writ, that we are still unable to shake off. The doctrine of von Neumann prevailed; it still dominates the *milieu.*

The last characteristic of the period of 1945-1952 is relates to the conduct of corporations like IBM, NCR and RCA, that until 1949 were hesitant to enter into this domain of calculating devices. Since then they make constant extensive efforts to control big chunks of the computer market, having realized that it has a sound economic future.

The most fascinating phenomenon occurred at the end of this period, in the USA in particular: the original developers of these devices failed as entrepreneurs and managers and in a short time they were dispossessed of their achievements and became professional consultants to corporations. Zuse had no better fate, nor did Mauchly and Eckert who, in the 1960s turned over the ownership of their firm to Siemens.

Another phenomenon accompanied the publication and dispersal of ideas linked to these devices. In 1947, the demand for the development of new methods of calculation for these devices was a growing. Awareness of this fact led to the establishment of the abovementioned Institute for Numerical Analysis at UCLA.

At the end of this period of up to 1952, the two main concepts of these devices crystallized, those of Turing and of von Neumann. These views had existed before and they exist, with minor variations, up to this day. Turing represents the concept of a thinking machine that imitates human reasoning with its artificial intelligence; von Neumann represents the concept of the computer as a very fast, multi-purpose calculating device. Both considered the computer a sequential machine, meaning that a finite series of operations (including feeding data) is carried out in consecutive order, in time, as one operation follows another. The original University of Pennsylvania team who worked on ENIAC were thinking at the outset in terms of a parallel machine, meaning the execution of several operations or functions simultaneously 'until came von Neumann and spoiled it' (Metropolis 1980, p. 457). A great deal of research is still undertaken by computer designers in efforts to overcome that very bottleneck, perpetuated by von Neumann *et al.* in their 'Trinity Paper'. The von Neumann bottleneck was described by John Backus in his 1977 ACM Turing Award lecture. I tend to agree with many others that a new revolution is dawning in the development of calculating devices in which the digital computer will exhaust itself and analog devices will return with new technologies. Still, interesting as this issue is and tempting as it may be to discuss, it passes well beyond the scope of the present study.

The Period After 1952

The central phenomenon that can be related to this period is the crystallization of computer science. From the ideological, technical point of view of the design of these devices, the solutions provided after 1952 did not differ very much from those obtained before 1952. What is termed 'the von Neumann architecture' still dominates the field as what I have dubbed 'St. John's Dogma'.

The difficult part here concerns the right way to deal with computer science. The very term 'computer science' raises difficulty. According to a broad definition, computer science is the body of knowledge that deals with the design, analysis, execution, efficiency and application of processes of information transformation. The basic question with which computer science occupies itself according to this definition is, what can be accomplished automatically? Computer scientists like P. J. Denning set the date of the establishment of computer science as a discipline in the mid-1940s, with the introduction (originally claimed by the author as 'invention') of an electronic computer possessing inbuilt internal storage. [19] For the computer science community, the issue of internal storage is vital to the definition of the computer. Given the extension of the definition of the discipline, and even of a narrower definition, computer science contains within itself deep roots in mathematics, in engineering and in logic.

Since the early 1950s, the computer-science community has remained torn between the two basic concepts left behind by Turing and von Neumann. von Neumann's approach, that most members of the discipline take for granted, deals with the science of calculating/computing, that is, the development of more accurate, efficient and faster techniques of computing. The minority of them view themselves from the viewpoint of the study of artificial intelligence. Definitions concern mere words; here it is not the word that matters but its use to designate the character of the discipline. The highly controversial occupation with the crystallization and definition of the contents and the aim of computer science is an issue by itself sufficient for much independent research, passing well beyond the defined scope of the present study.

Summary

In this section of the book I focus on the period of 1945-1952 that had a profound effect on all that was to come, virtually up to this day. What came out of those developments and how was this unity formed among the various places, meaning, when did that awareness or notion begin that the various separate developers were occupied with the same thing?

The War's end brought to light and to fame the work of those developers and their associates who were occupied with the development of computing, storage and control components. This exposure enabled publications about this type of calculating device to be released in the various media and presented at meetings and conferences, on which the original developers had great influence. It was also this exposure that brought about the awareness that the developers in the various places had been occupied with the same kind of calculating devices all along.

And what accrued from all of this? This question is controversial. As for the design of these devices, we know that electronic technology in its binary form and internal storage, according to von Neumann's architecture, finally and completely prevailed to dominate the domain. Today's computer science was the result of all this. But, before getting so far ahead of ourselves, we can mark two main cornerstones along the way. In the first phase, until the early 1950s, what resulted from these automatic program-controlled digital calculating machines was a multi-purpose device and no more. In the second phase, during the 1960s, the understanding surfaced that this device was not merely a comprehensive mathematical calculating means of various kinds, but a means for processing information in general, crystallized and finally dominated the general perception. At last we arrive at the modem definition of the very word 'computer' as a device for information processing, even though the term 'computer' for this type of device still expresses the primary aim of performing computations. Nevertheless, it was already obvious to anyone since the 1970s that the capacity of this device is more in the manipulation of data or information processing than the mere capacity of performing mathematical calculations. Still, even the Hebrew name of the computer, *'machshev'*, which in its practical meaning is derived from the verb 'to think' (reckon, reasoning), reflects the much better the primary dispute that started in the early 1950s: can machines think? To repeat, here arrives the terminus of the scope of the present study.

General Summary

In the present study I have attempted to identify and trace the theoretical and technical factors that may have led to the multiple, simultaneous emergence of the automatic program-controlled digital calculating machines in the USA, the UK and Germany during the period 1935-1945.

Resulting from the investigation of the development of the automatic program-controlled digital calculating machines in the period 1935-1945 in the USA, the UK and Germany, the following conclusions emerge:

1. The name 'automatic program-controlled digital calculating machine' gives an extremely apt description of the calculating devices that were developed during the period 1935-1945. From the analysis of the memoranda written on the subject by the various developers during that period—Zuse (1936); Aiken (1937); Stibitz

(1940); Atanasoff (1942); Mauchly (1942) and others, in which they propose and describe their ideas and designs—it is quite clear that the devices were built in order to solve a series of certain mathematical problems, which may be classified into two groups:

a. Algebraic linear equations with many unknown factors. Two different versions—of Zuse and of Atanasoff— adopted solutions by matrix algebra.
b. The solution of differential equations— total or partial—by the Raphson-Newton method, i.e. use of iterations. This approach was adopted by Aiken and Mauchly.

In these calculating devices, continuous and sequential control was adopted according to a format and algorithm lacking the conditional branching loop in the program. In the best of cases, this was achieved in the hardware, the British Colossus and Stibitz's 'computer' being exceptions: Colossus was designed as a sorter of alphanumeric information and the 'complex computer' (Bell Model I) of Stibitz was designed to solve complex numerical problems.

Hence, none of these automatic program-controlled digital calculating machines developed during the period 1935-1945 meets the criteria of the computer as formulated in the 'First Draft' or 'Trinity Paper', and nothing suggested in Turing's 1936 paper on what is known today as the Turing Universal Machine that represents the properties of the modern computer in the highest possible order. Nevertheless, I tend to believe Zuse, Mauchly, as well as Eckert and Huskey that the matter of internal storage looked to them as self-evident. What was lacking was the logical formalization of that internal storage principle, and that was provided by von Neumann or by Goldstine—on von Neumann's behalf or in his name. Or, as Eckert put it in engineering terms:

> 'It has always been disconcerting to me that von Neumann would listen to us, discuss many of our ideas with us, and rewrite them with the Neuron Notation that McCulloch and Pitts had used on some neuron studies ... I can only guess that he felt that ... he had translated everything we were doing from engineering terms to neural terms...' [1].

Still, all the devices discussed here fall in the category and definition of the automatic program-controlled digital calculating machine. Moreover, history indicates that this is a case of a multiple discovery. Hence, none of the automatic program-controlled digital calculating machines developed during 1935-1945 meets the criteria of the computer as described in the 'First Draft of a Report on the EDVAC' or the 'Preliminary Discussion of the Logical Design of an Electronic Computing Instrument'.

2. There were two fundamental approaches to designing the machines during 1935-1945. One is represented by Zuse, Atanasoff and, to a certain extent, the Colossus team, based on their own development and construction of components. The second, represented by all the others, was the development and construction of the device by adapting existing and available components and their incorporation into a novel machine.
3. Popular histories of the computer that describe the development as a continuous sequential narrative starting from the abacus or the mechanical digital calculator, e.g., *The Computer from Pascal to von Neumann of* H. H. Goldstine, 1972, have no basis in facts. The developers of 1935-1945 operated with no knowledge of the work of their predecessors, especially Babbage. The only possible exception is Alan Turing. Evidence indicates, though in my opinion unreliably, that Turing knew of Babbage and admired him. In truth, one may state a contradiction blithely, without being aware of doing so. The adoption of Babbage as a 'computer pioneer' and as a 'spiritual mentor' or as the 'father of the computer' was declared in retrospect; it constitutes a part of the mythology created by the developers. It was mainly Aiken who was responsible for creating the 'Babbage tradition', as a 'computer pioneer'; on this he succeeded in misleading most researchers.
4. During the 1930s, many people were preoccupied with switching, and unconsciously applied many of the ideas of Boolean algebra and of symbolic logic. At that time, the building of such circuits was considered an 'art,' an intuitive understating not yet crystallized into a discipline. The craft of electrical circuits was by trial and error on accumulated experience.
5. No evidence whatsoever indicates that the design and development of these automatic program-controlled digital calculating machines were in any way influenced by the well-known work of Turing (1936), nor by the works of other mathematical logicians such as Gödel, Church, Post, and Kleene. On the contrary, it is known that the machines were developed independently and without conscious knowledge of Turing's work, the programs of Hilbert or the *Principia Mathematica* of Russell and Whitehead.
6. There is no doubt that the events after 1945 derived directly from what occurred during 1935-1945 in the history of the computer.

However, it was not in direct dependence on a specific automatic program-controlled digital calculating machine (computer) such as ENIAC or the Harvard Mark I, even though this has been claimed in various studies. Rather the dependence was on all the machines discussed here.

7. The automatic program-controlled digital calculating machines (or the digital computers, as claimed) were invented not because of the need for faster operations in scientific or commercial calculations. Specific solutions were found for specific needs—usually by analog instruments.

   The development of the automatic program-controlled digital calculating machine is one of the examples in history where the ideas for its design and development derived from its technology. It was the existence, availability and reliability of the components that inspired inventors. It was the technology, in particular the binary technology, that dictated the developments and ideas that consequentially derived from it. This is no attempt to suggest a deterministic view; it is not the claim that everyone dealing with binary technology must develop such machines. The developers asked questions such as, what can be done such and such technology that we have? What of these possibilities is new? Such questions are unusual. They are leapfrogs on the stage that I call technological drag, in which new technology is used for the performance of old tasks.

   I find a great similarity between the present case and the case of the development of the electro-magnetic telegraph. Samuel Morse, for example, immediately grasped that the electro-magnet that he saw during experiments in London was a tool that enabled the transmission of information. Gauss understood this too, as did Weber, Wheatstone and others. The answer here is to the question, in effect: well, we have a new tool (in this case, electro-magnetic phenomena); what can be done with it? What remained for Morse to do after he had determined that this was a new tool for representing information, was to invent an appropriate code (with Alfred Vail)—in this case a binary code with an unfixed number of signals, to render the various symbols or characters, and a means for the transformation and transmission of this code in that new technology.

8. My assumption is that World War II had only an indirect influence on the development of the automatic program-controlled digital calculating machines. the development of some of them resulted

from the War, while the development of others was stopped or shelved as the result of the War.

9. I did not succeed in tracing the exact causes that led to the emergence of the automatic program-controlled digital calculating machines specifically during 1935-1945 in Germany, the UK and the USA. This particular issue was carefully analyzed in Part III, in which thirteen alternative answers were presented, some offered by others, some by myself. Most of these answers were found incorrect and refuted because they simply did not fit some recorded events. Nevertheless, some of the answers are still debatable and under dispute; in Part II I devoted a separate discussion for Answer 14.
10. The analyses of the individual and the collective biographical portraits of the developers did not indicate that they were possessed with relevant unique characteristics, skills or professions. Their common characteristic was the adoption for their machines of binary technology, of two distinct states, and the abandonment of the traditional wheel as a calculating and storage component. This was so even when some of them imitated the wheel with other techniques. Moreover, I must mention, albeit with reservations, that, consciously or not, those developers used information as a commodity, even though their published sources and memoranda hardly indicate this.
11. Furthermore, the attempts of Babbage to design and develop his engines and succeeding attempts to design and develop similar calculating means suggest that a certain process was under way of crystallizing the concept that information can be represented by concrete entities that can undergo manipulations.

To summarize, in addition to the reopening of the discussion on the problem and the re-examination of existing and new sources, my contribution lies in limiting the discussion of the issue of the simultaneous and multiple appearances of the automatic program-controlled digital calculating machine, or the history of the digital computer, by refuting most of the answers given until now and concentrating on several alternative answers. To my mind, the focus of the discussion of these answers is the main achievement of the present work.

Accordingly, the discussion of the answers to the question, why the automatic program-controlled digital calculating machines were developed in Germany, the UK and the USA during the period 1935-1945, did not help to trace the causes that led to the development of these machines at that specific time and in those countries. I shall therefore present here briefly only six of the alternative answers to the question, those that remain controversial. Although some arguments may refute these answers, I nevertheless found them at this stage preferable, within certain limitations, to the other alternative answers given in the summary of Part I. The alternative answers that are still disputable are as follows.

1. The automatic program-controlled digital calculating machines were developed during the period 1935-1945 in Germany, the UK and the USA because they were needed for scientific and engineering computations.
2. The automatic program-controlled digital calculating machines were developed during the period 1935-1945 in Germany, the UK and the USA because the limitations of the conventional calculating means constituted an incentive to the developers to seek new ways to overcome these limitations.
3. The automatic program-controlled digital calculating machines were developed during the period 1935-1945 in Germany, the UK and the USA because the body of knowledge in those countries was then at a similar stage of development. This led the various developers to ask similar questions that produced similar solutions.
4. The automatic program-controlled digital calculating machines were developed during the period 1935-1945 in Germany, the UK and the USA because, during the 1930s, conditions evolved to allow components, tools and techniques previously available, to merged and incorporate them, thus leading to the development of new tools with a greater potential than each of the older components provided individually.
5. The automatic program-controlled digital calculating machines were developed during the period 1935-1945 in Germany, the UK and the USA because for over 100 years there had been parallel developments in a small number of relevant fields of technology, such as communications, electricity, electronics and symbolic logic.
6. The automatic program-controlled digital calculating machines were developed during the period 1935-1945 in Germany, the UK and the USA because a new conceptual tradition emerged from a special type of strategic convergence that brought together several conceptual traditions of technologies and ideas that were necessary for it and that were supported by economic, political and academic interests.

We tend towards linear narratives, whereas outcomes result, dare I say, from karma and dharma, the confluence of favorable and unfavorable conditions to possible outcomes, that bring all of the above factors together. This would explain the elusiveness of a simple historical plotline for these momentous developments.

To repeat, the above answers are debatable. Nevertheless, if, most unwillingly, I am forced to adopt any of those answers, then information and figures seem to me to indicate that Answers 4, 5 and 6 provide the best explanations known so far for the question raised here, despite the arguments that refute them. I admit that at the beginning of my research I was strongly inclined to adopt Answer 5 as the preferred solution. However, as I delved deeper into the matter, I found that this answer also remains open to further debate, even though its refutations are severe.

Joseph Agassi comments:

In editing this rich volume, I have refrained from commenting on its contents. I make one exception here as I add this note on a point too important to neglect. Dr. Arbel's arguments against Answer 5 are strong, well-worded; being comprehensive, they are obviously valid. Yet they are answerable and the answer invite extensions to this discussion.

Intellectual debt often comes through secondary sources. The paradigm here is Einstein's debt to Michelson of which he was utterly unaware when he wrote his classic 1905 paper on special relativity. See Gerald Holton's classic 1969 paper, 'Einstein, Michelson, and the "crucial" experiment', *Isis* 60: 133-197. Nearer home is the enormous debt of Bertrand Russell to Gottlob Frege that he could not possibly suspect as it came to him through contacts with Giuseppe Peano and others who had no occasion to mention Frege in his presence. And then there is the huge class of forgotten debt that Robert K. Merton called *kleptomnesia*.

ENDNOTES

Introduction

1] John von Neumann, ‘First Draft of a Report on the EDVAC’, Contract no. W-670-Ord-497, Moore School of Electrical Engineering, University of Penn. (30 June 1945). Reprinted in Randell (1973). I have nicknamed ‘Trinity Paper’ the report prepared within the framework of the conditions of contract W-36-0340-Ord-7481 between the Research and Development Service Ordnance Department, US Army and the Institute for Advanced Studies, Princeton University. The full bibliographic citation of the report is, A. Burks, H. H. Goldstine, J. von Neumann, ‘Preliminary Discussion of the Logical Design of an Electronic Computing Instrument’ part 1, vol. 1, Institute for Advanced Study, Princeton (28 June 1946). (2nd edition, 2 Sep. 1947). Reprinted in Abraham Haskel Taub, ed., *John von Neumann: Collected works*, vol. 5, Oxford: Pergamon (1963), pp. 34-39. Extracts reprinted in Randell (1973).

2] T. M. Smith, ‘Some Perspectives on the Early History of Computers’ in Z. W. Pylyshyn, ed., *Perspectives on the Computer Revolution*, Englewood Cliffs, NJ: Prentice Hall (1970), pp. 7-15.

3] H. H. Goldstine, *The Computer from Pascal to von Neumann*, Princeton, NJ: Princeton University Press (1972).

4] Nancy Stern, *From ENIAC to UNIVAC: A Case Study in the History of Technology*, PhD Dissertation, State University of New York at Stony Brook (1978). Based on it is Nancy Stern, *From ENIAC to UNIVAC: An Appraisal of the Eckert Mauchly Computers*, Bedford, MA: Digital Press (1981)

5] J. V. Wells, *The Origins of the Computer Industry: A Case Study in Radical Technological Change*, PhD Dissertation, Yale University (1978).

6] P. E. Ceruzzi, *The Prehistory of the Digital Computer 1935-1945: A Cross Cultural Study*, PhD Dissertation, University of Kansas (1980). Based on it is Ceruzzi, *Reckoners: The Prehistory of the Digital Computer, from Relays to the Stored Program Concept, 1935-1945*, Greenwood Press (1983).

7] B. O. Williams, *Computing with Electricity 1935-1945*, PhD Dissertation, University of Kansas (1984).

8] W. F. Aspray Jr., *From Mathematical Constructivity to Computer Science: Alan M. Turing, John von Neumann and the Origins of Computer Science in Mathematical Logic*, Ph. D. Dissertation, University of Wisconsin-Madison (1981).

9] T. P. Hughes, ‘ENIAC: Invention of a Computer’, *Technik Geschichte*, 42, p. 148 (1975).

10] M. G. Stevenson, 'Bell Labs: A Pioneer in Computing Technology', Part 1: 'Early Bell Labs Computers', Bell Labs Inc., p. 3 (1974). The original apparently exists in Bell Labs Record 51, pp. 344-351 (Dec. 1973).

11] See Erich Jantch, *Technological Forecasting in Perspective.* Paris: Organization for Economic Cooperation and Development (Oct. 1966), p. 65. See also A. E. Musson, *Science, technology and economic growth in the eighteenth century,* University Paperbacks (1972), p. 15.

12] T. P. Hughes, 'The Development Phase of Technological Change' in *Technology and Culture*, vol. 17, no. 3 (July 1976), p. 427.

13] *Ibid.*, p. 429.

14] *Ibid.*

15] *Ibid.*

16] Merton wrote extensively on this subject. The claim that the scientific discovery is in essence multiple is a contention that he raised publicly in a lecture given in 1961, during the conference of the American Philosophical Society to commemorate the 400th anniversary of Francis Bacon's birthday. R. K. Merton, 'Singletons and Multiples in Scientific Discovery', *Proceedings of American Philosophical Society*, vol. 5 (Oct. 1961), pp. 470-486.

Chapter One

1] On the history of computer see also T. M. Smith, 'Some Perspectives on the Early History of Computers', in I. W. Pylyshyn, ed., *Perspectives on the Computer Revolution*, Englewood Cliffs, NJ: Prentice Hall (1980), pp. 5-15; R. W. Hamming, 'We would know what they thought when they did it', in Metropolis (1980), pp. 3-9; K. U. May, 'Historiography: A Perspective for Computer Scientists', in Metropolis (1980), pp. 11-18; T. M. Smith, 'Origins of the Computer', in M. Kranzberg and C. Pursell, eds., *Technology in Western Civilization*, vol. 2, pp. 302-323, NY: Oxford University Press (1967); and H. H. Goldstine, *The Computer from Pascal to von Neumann*, Princeton: Princeton University Press (1972), Preface.

2] The influence of Babbage on the early developers of the automatic program-controlled digital calculating machines engages many discussions. Metropolis and Worlton, 'A Trilogy of Errors in the History of Computing',*Proc. First USA-Japan Computer Conference October 3-5, 1972,* AFIPS, Montvale NJ (1972), pp. 683-691, report this evidence: 'Awareness of Babbage's work has suffered no long gaps ... what is surprising, then, is not that some people were "aware" of Babbage's work, but that others were "unaware of his work".' Even this skepticism does not express properly my own claim that all the developers of the automatic program-controlled digital calculating machines acted independently, all in total ignorance of Babbage's effort. For references to other views on this issue, see Chapter 2.

3] William J. Worlton, 'Pre-Electronic Aids of Digital Computation', in S. Fernbach and A. Taub, eds., *Computers and their Role in the Physical Science*, NY and London: Gordon Breach Science Pub. (1970), pp. 11-50. See also Randell (1973), Bibliography; Li Shu-Tien, 'Origin and Development of Chinese Abacus', *Jour., ACM*, vol. 6, no. 1 (1959), pp. 102-110.

4] See W. Worlton (1970, pp. 26-50), based heavily on D. E. Smith, *History of Mathematics*, vol. 2, NY: Dover Publ. (1958), pp. 156-190. This is a reprint of the 1929 edition.

5] André Wegener Sleeswyk, 'Vitruvius' Odometer', *Scientific American* (Oct. 1981), pp. 158-171. In the ten books of Vitruvius' *On Architecture* are found various versions of devices to measure distances (from the Greek *'hodos'*, 'way' and *'metron'*, 'measure'). In book X, Chapter IX, he describes two versions of the odometer: one was for service on land, the other a marine version. Marcus Vitruvius Pollio was a military engineer and architect of the Roman Empire in about 20 BC. He describes a four-wheeled carriage with a toothed cogwheel gear mechanism, and the distance covered was measured in a ratio of 1:400. A complete rotation covered a distance of 1000 passes, equivalent to 1650 meters. Every Roman mile was marked by a pointer. The erection of milestones is mentioned in 250 BC and was made compulsory by a decree of the tribune Gaius Sempronius Gracchus in 123 BC.

The English terms 'engine', 'engineer' and 'ingenious' are derived from the same Latin root, *'ingenerare'*, meaning 'to create'. The early English verb 'engine' meant 'to contrive'. Thus, the engines of war were devices such as catapults, floating bridges, and assault towers; their designer was the 'engineer', or military engineer. His counterpart was the civil engineer, who designed structures, streets, water supplies, sewage systems, etc. *Encyclopedia Britannica* 1974 edition, *Macropedia*, vol. 6, p. 861, Art. Engineering.

6] According to Bernard Gille, *Les Mécaniciens Grecs, La Naissance de la Technologie*, Paris: Edition du Seuil (1980). See a review thereof in *Technology and Culture* (Oct. 1981).

Archytas of Tarentum was a key figure during the 4th century BC. The graduates of Alexandria built fortifications, port, war machines, pumps, ships, water clocks and temples, but they also constructed various gadgets for minor uses. Two groups formed from these graduates:

> A. That which applied the lever, wheel, wheel transmission, screw and wedge.
>
> B. That which used pneumatics from which the control and feed-back mechanism originated, based upon a wheel and axis feed-back mechanism of the oil lamp of Heron.

T. M. Smith (see note 1 above) cites a description by Heron of Alexandria of the transfer of carry by means of a toothed cogwheel gear mechanism.

7] Derek J. de Solla Price, 'An Ancient Greek Computer', *Scientific American*, vol. 200 (June 1959), pp. 60-67.

8] Sigfried Giedion, *Mechanization Takes Command: A Contribution to Anonymous History*, the Norton Library, NY (1969). See also an excellent book on this topic by David S. Lands, *Revolution in Time: Clocks and the Time Making of the Modern World*, Cambridge MA: Belknap Press (1983), pp. 54-70.

9] From D. E. Smith (1958), Endnotes N3 and N4, p. 202. Also see: M. R. Williams, 'From Napier to Lucas: The use of Napier's Bones in Calculating Instruments', *Annals of the History of Computing*, vol. 5, no. 3 (July 1983), pp. 276-296, as well as E. M. Horsburgh, ed., *Napier Tercentenary Celebration: Handbook of Exhibition*, Edinburgh: Royal Society of Edinburgh (1914). This is a collection of papers prepared for this event. It was also published as a hardcover and under a different title: *Modern Instruments and Methods of Calculation: A Handbook of the Napier Tercentenary Celebration Exhibition*, London: G. Bell & Sons (1915). Another edition contains articles in German and in Turkish not included in the other editions due to the outbreak of the World War I: Cargill G. Knott, ed., *Napier Tercentenary* (1915).

Due to the scarcity of copies of the above handbook, a facsimile of Horsburgh's book reappeared on the initiative of the Charles Babbage Institute in the MIT's project in the series *History of Computing*. Part B of the book includes several descriptions of instruments based upon Napier's rods. However, there is no mention there of Napier's *Promptuarium Multiplicationis*. As some scholars have claimed, strong evidence suggests that Napier's is the first calculating machine. See, especially, W. F. Howkins, 'The First Calculating Machine (John Napier, 1617)', *The New Zealand Math. Soc. Newsletter*, no. 16 (Dec. 1979), supplement 1-23.

10] Found in M. R. Williams (1983), page 280 (see also note 9).

11] The example is taken from E. M. Horsburgh, *Calculating Machines*, pp. 6-9.

12] Von Freytag Löringhoff, *'Eine Tübinger Rechenmaschine aus dem Jahre 1623'*, *Heimat-kundliche Blätter für den Kreis Tübingen* 11: 3 (1957), pp. 25-28 offer a detailed description of Schickard's machine. It also quotes his letters to Kepler that refers to a machine that he named 'a computing clock'.

M. R. Williams (1983), p. 284, reports that when several researchers tried to create a complete collection of Kepler's writings, the drawings of Schickard's machine were discovered on a piece of paper that served as a bookmark in a copy of Kepler's *Rudolphine* astronomical tables found in the Pulkovo Observatory Library (in the vicinity of St. Petersburg).

On the celebration of the three-hundredth anniversary of Schickard's birthday see *Nature*, (Oct. 19, 1935), p. 636, as well as Hyman (1982), pp. 47-48.

13] M. R. Williams (1983), pp. 291-293.

14] See note 7 above.

15] Goldstine (1972), note 8, p. 8.

16] The origin of the tradition of calculating machines ensuing from Pascal probably began with D. Diderot, Art. *Arithmetique (Machine)*, *Encyclopédie ou Dictionnaire raisonné des sciences, des arts et des métiers*, Paris (1751), tome 1, pp. 680-684. This seems the first satisfactory account of the mechanism of Pascal's machine, in particular of the carry component. This tradition lived on in the writings on calculating devices of the Frenchman Maurice Philbert d'Ocagne (1862-1938) and the German Rudolf Mehmke (1857-1944), who at the end of the 19th century and the beginning of the 20th century wrote the entry 'Numerical Calculations' in the following encyclopedias: *Encyclopédie des sciences mathématiques pures et appliquées*, tome 1, vol. 4 (1908), pp. 196-320; *Encyklopädie der mathematischen Wissenschaften mit Einschluß ihrer Anwendungen*, Leipzig, vol. 1, part 2 (1900-1904), pp. 952-978.

This tradition is also found in the first eight editions of the *Encyclopedia Britannica*. Of all editions, those from the 9th of 1876 up to the edition of 1974, the entries dealing with calculating tools is informative about the growth of the linear tradition of continuity in the calculating machines which coincides with that in computer history. In the 9th edition (1876) of the *Britannica* the entry 'Calculating Machines' has only two pages. It was edited by Professor P. R. S. Land, a graduate in mathematics from the University of St. Andrews. That entry has a short review of about ten lines on the abacus, Napier rods, the slide rule, and Pascal's and Leibniz calculating machines. The rest of the entry focuses on the ideas of Babbage and of Scheutz on the difference engines. Concluding the entry are a few lines recalling the development of analog calculating means for the solution of differential equations. For more comprehensive information, readers are directed to the 1871 *Insurance Cyclopaedia* by Cornelius Walford.

Although the 10th edition (1902-1903) is expanded by several volumes, it has no change at all in the entry 'Calculating Machines'. By contrast, the 11th edition (1910-1911) includes the entry 'Calculating Machines' that stretches on for 11 double-sided pages. The editor is O. M. F. Henrici, professor of mathematics and mechanics at the London Central Technical College. The entry begins with a comprehensive discourse on the technical principles of the mechanical calculating machines applying toothed-cogwheel gear mechanisms. The abacus is not mentioned in this entry; it appears instead in a separate entry. In that entry three pages provide information on counting techniques and the devices developed according to them. Only a few standalone lines are dedicated to the machines of Babbage and Scheutz. The written account focuses on calculating devices that achieved commercial success, such as the Brunsviga and the Millionaire. The authors rely on German sources, particularly on Mehmke (1901-1904; *Ency. of Math.*) and on Walther von Dyck, *Catalog of Calculating Machines*. The section on the slide-rule occupies a whole page. Most of the entry, eight full pages, discusses continuous devices, as this was then the name for the analog devices, or for integrators of all types; strangely, the slide-rule is not included among them. It is important to note that the term 'Analog Calculation-Devices' for continuous calculating devices had not yet been adopted.

The 14th edition (1929) of the *Britannica* is an abridged version of David Baxandall's *Catalog of Calculating Machines and Instruments* (1926). The entry for calculating machines stretches on for nine pages (553-545) as compared to the eleven pages of the 11th edition. Here, for the first time, Herman Hollerith's punch and tabulating equipment is mentioned. Baxandall's *Catalog* comprises three chapters: Chapter I, Calculating Machines and Instruments; Chapter II, Drawing Instruments; and Chapter III, Mathematical Models and Apparatuses. The introduction to the catalog gives a detailed account on the establishment and development of the London Science Museum and its calculating-machines collection that commenced with Charles Babbage's collection, presented by his son Herschel in 1905. The catalog provides a description of the calculating devices of Napier, Pascal, Morland, Leibniz, Thomas, Bollée, Scheutz and Hollerith.

In the 1949 edition of the *Britannica*, an update of the 14th edition has five written pages and two pages of photos of various calculating devices, including Napier rods, the calculating machines of Pascal, Leibniz, Thomas, Odhner, and Burroughs, the slide-rule and some punch equipment. Of the five written pages, four give an account of the development of calculating devices that possess toothed-cogwheel gear mechanisms; devices based on Napier rods are represented extensively. For the first time, electro-magnetic and electronic calculating means are described. There is also a short section on devices with relays with references to the devices developed at Bell and IBM Laboratories. There is also an account of the applications of vacuum tubes for calculations: 'Many of these developments were undertaken during World War II, complete information is not yet available to the public' (page 552). Half a column deals with punch equipment, one column on the difference and analytical engines and, lastly, one page on non-digital or continuous calculating means. Just one reference is made there to the slide-rule. This edition already has a separate entry for 'Mathematical Instruments'. That entry covers continuous devices such as analyzers and integrators of various types, designated for such particular tasks as fire control or solutions of linear equations. The bibliography in this entry is extensive and varied; it is derivative of publications prior to 1928. In the 1946 edition, treatment of calculating devices is divided into two separate entries:

1. Computing Machines, Electronic. It deals for the first time with electronic computers, digital and analog. It is four pages long. It makes reference to the issue of accuracy, specific and multi or general purpose calculating devices, binary notation, switching means, speeds of operations, means for data storage and scientific and business applications.

2. Office Machines and Appliances. This item covers less than three pages, and includes a short paragraph within a column that deals with computing and accounting machines, as well as with punch and tabulating devices termed classifying and selecting machines. Its section on office calculating machines includes a superficial account on their operation and application for office work.

The 1972 edition of the *Britannica* has calculating machines in the entry 'Office Machines', where almost a column is devoted to reviewing the development of calculating means in the linear tradition, 'From the Abacus to Babbage and the Harmonic Analyzer of Lord Kelvin'. Accounting machines occupy a separate paragraph of a few lines. By contrast, the section on classifying selecting machines is extended to two pages. This edition contains a separate entry for the 'Electronic Computer'.

The 1974 edition of the *Britannica* has an entry on office machines and calculating machines. It is an extended version of the 1972 item. The entry 'Computer' is expanded extensively to thirteen pages. It has a section of two pages that deals with the history of computing devices, in the traditional linear approach. A second section of five pages occupies itself with the principles of analog and digital computers. A third section six pages long focuses on languages and programming. The bibliography annexed to that entry is rich and extensive. It concentrates mainly on the social and economic aspects and the influences of the application of the computer to commerce.

My impression is that the 1937 memorandum of Aiken is responsible in part for the adoption of the modern version of the traditional linear approach. His eminent position in the computer science community during the period from 1940 up to the 1950s that resulted from the establishment of the Harvard Computing Laboratory in which his machines were constructed, enable many of his disciples to organize several international conferences on these machines. The linear view of Aiken appears, almost word for word, in many books on computer science and in the history of computing. Aiken and Hopper, 'The Automatic Sequence Controlled Calculator'. *Electrical Engineering*, vol. 65 (1946), pp. 384-391, 449-454 and 522-528 is reprinted in full in Randell (1973), pp. 199-218. From this paper we may learn that Aiken (1946) used references taken from D'Ocagne (1905) and Horsburgh (1914), as well as from the Baxandall *Catalog* (1926), *Calculating Machines and Instruments*, prepared for the London Science Museum, of which he was then the curator of the calculating machines collection. In his historical preface of the memorandum of 1937, Aiken used Baxandall as his main source. An abridged version of the Baxandall *Catalog* was used in the 14th *Britannica* edition (1929) for the entry 'Calculating Machines'; the Baxandall *Catalog* of 1926 was updated in 1976 by Jane Pugh, then the curator of the collection. She made no significant changes in the written account.

This is also correct as to Aiken's awareness of Babbage's work. The Aiken and Hopper article (1946) in the relevant bibliography makes reference to Babbage's autobiography, *Passages from the Life of a Philosopher* (1864). Aiken learned about it only after 1942. He possessed two copies of it; one was presented to him by Bryce from IBM (the famous engineer who worked with Aiken on Mark I); the other was given to him in Britain by L. Comrie in 1946. All that happened one day when one of the technicians told Aiken about fragments of a calculating device that turned out to be original components of Babbage's difference engine. These were preserved at Harvard University, presented to them by Babbage's son on the occasion of the 250th anniversary of Harvard's foundation, but not before they agreed to cover the shipment expenses. On that 'fragment of Babbage's difference engine' Aiken and Hopper (1946) only and also provided a picture of the calculating wheels designed by Babbage (1834). A more detailed account on the Aiken-Babbage issue appear in Part II above, in the presentation of Aiken's biography. Brian Randell, in his article 'Ludgate's Analytical Machine of 1909' (1971), pp. 317-326, raises a similar conjecture as to Aiken's awareness of Babbage and to another designer of the analytical engine, the Irishman Percy Ludgate:

> 'Interestingly enough, a memorandum written by Aiken (1937) outlining plans for an automatic calculating machine, mentions Ludgate in addition to describing Babbage's work on the difference and analytical engines. However, the reference, whose wording closely follows that used earlier by Baxandall (1926), merely lists Ludgate amongst the designers of difference

> engines, so there is little reason to suppose that Aiken was familiar with Ludgate's plans' (p. 318).

To repeat, on the Aiken-Babbage issue, Randell could extend his supposition to Ludgate's plans as well.

17] See E. W. Phillips, 'Binary Calculations', *Journal Institute of Actuaries*, vol. 67 (1936), pp. 187-221. Extracts are reprinted in Randell (1982), pp. 303-314; Randell (1973), pp. 296-297; as well as in Bertram Vivian Bowden, *Faster Than Though*, Sir Isaac Pitman & Sons (1953), p. 3; M. Kormes, 'Leibniz on his Calculating Machine' in D. E. Smith, *A Source Book in Mathematics*, NY: McGraw-Hill (1929), pp. 173-181. This a translation of *'Machina Arithmetica in qua nun Aditio et Subtracio sed et Multiplication Nulla, Division Vero Paene Nulla Amini Labore Perangantur'* (1685). It is an account of a machine capable of performing the four basic arithmetical operations. In the Leibniz Hanover manuscript collection, a manuscript of March 15, 1679 titled *'De Progressione Dyadica*—Pars I*'* discusses binary notation as well as the possibility of designing a mechanical binary calculating device using moving balls to represent binary digits. See also Randell (1973), p. 425 or Randell (1982), p. 486.

Louis Couturat, *La Logique de Leibniz*, Paris (1901), pp. 115-116, refers to different letters that mention Leibniz's machine, but with no details. Couturat emphasizes Leibniz's zeal and aspiration for a universal mathematical and linguistic calculus that could be mechanized. This meant finding an overall solution, based on a language or a logic computable in principle, and capable of being imprinted in hardware—i.e., in a machine that enables the decision in any dispute. Leibniz discussed a machine, however, not a mechanical process or format, an algorithm. J. E. Hofmann, *Leibniz in Paris 1672-1676, His growth to mathematical maturity*, Cambridge: Cambridge University Press (1974), includes a highly detailed account on binary notation. See also Wilfried de Beauclair, *Rechnen mit Maschinen*, Braunschweig: Friedrich Vieweg & Sohn (1968), p. 22.

18] An account of Bacon's A-B binary concept is found in his ABC essay: Speeding, Ellis and Heath, eds., *The works of Francis Bacon, in 14 Vol.*, London (1857-1874), vol. 2, pp. 83-87; see also F. G. Heat, 'Pioneers of Binary Coding', *Jour. Inst. Of E. E.*, vol. 7, no. 81 (Sep. 1961), pp. 539-541. It is an account on Bacon's A-B binary notation taken from his *De Augmentis Scientiarum* (1623). Additional and more detailed descriptions of the application of binary notation by others can be found in A. Glaser, *History of Binary and Other Non-Decimal Numeration*, Tomas Publ. Revised Edition (1981), as well as in 'Addendum on the Book of Change and the Binary Arithmetic of Leibniz' in J. Needham, *Science and Civilization in China*, Cambridge: Cambridge University Press (1958), vol. 2, pp. 340-344.

In modern times, other than Morse, Benjamin Peirce (1809-1880) proposed in an 1876 memorandum to the Survey Department of the US Coast Guard to adopt 'A New System of Binary Arithmetic'. It was a binary code—a hexadecimal (base of 16) binary code—based on horizontal bars (lines), based on what Leibniz learned from the Chinese hexagrams (see Needham above).

19] J. E. Hofmann (1974), pp. 34-35: Leibniz did not manage to meet his obligation to construct a more advanced version of his calculating machine, injuring his prestige and embittering his relations with the Royal Society.

20] *Ibid.*, p. 304.

21] I. A. Apokin and L. E. Maistrov (1974), *Rasvitie Vyichislitelnyich Mashin. Nauka*, Moscow (1974), Chapter 2 offers an account on Jakobson, Odhner, Schickard, Pascal, Leibniz and others. In another article, *Voprosy Istor, Estestvoznan* I Techn. vir. 1 (26) (1969), pp. 35-39, they describe the Yavne Jakobson a machine. A review of this article is in C. J. Scriba, Review of Maistrov LE and Cenakal VL: *A very old calculating machine.' Math. Reviews* 40.3 (1970), pp. 456-7.

22] H. H. Goldstine (1972), p. 8, note 10. Goldstine reports that he has learned about Abraham Stern's work from W. M. Turski of the Polish Academy of Sciences.

23] Taken from D. E. Smith (1958), p. 156. The source on which Smith relies is Christian Ludwig Gersten, *Phil. Trans.*, Abridgment, 1747, VIII, 16. Most historians of mathematics have more or less rewritten a section of one chapter on calculations by means of calculating devices in Smith (1958) Chapter III, Mechanical Aids of Calculation. It stretches on forty pages. Of these, thirty are devoted to the abacus, and six to finger counting. Its section that deals with modern means of calculations occupies five pages, of which half a page deals with Napier rods, two pages are designated for mechanical calculating machines, and the other two deal with the slide-rule. Smith's *A Source Book in Mathematics* (1929) has a discussion of several pages on the Napier rods and the calculating machines of Pascal and Leibniz (pp. 165-185). The first pages of the book include an article that explains the 'Gelosia' multiplication method.

24] *Britannica*, 1974 edition, vol. 4, Art. 'Calculating Machines', p. 549.

25] *Ibid.*, p. 550.

26] Mehmke (1901-1904), pp. 958 and 980-981: *Britannica*, 1949 edition, vol. 4, Art. 'Calculating Machines', p. 551, column B.

27] René Moreu (1984), p. 19

28] *Ibid.*

29] *Britannica*, 1949 edition, vol. 4, p. 552.

30] Moreu (1984), p. 20; and *Britannica*, 1949 edition, p. 550, column B.

31] *Ibid.* (Moreu & *Britannica*).

32] *Ibid.*, p. 551.

33] Williams, M. R. (1976). 'The difference engines', *The Computer Journal*, *19*(1), 82-89, 81.

34] Confusion persists as to the original date of design of Müller 's difference engine. The design was made probably by 1783 while the publication of the plea for financial support was made in 1786—in Johann Helfrich von Müller's *Beschreibung seiner neu-erfundenen Rechenmaschine, nach ihrer Gestalt, ihrem Gebrauch und Nutzen. Frankfurt und Mainz: Varrentrapp Sohn und Wenner,* edited by Ph.-E.

Klipstein (1786). The last chapter there has an account on Müller's difference machine (of 1783) and an appeal for financial support. The purpose that this machine was meant to serve was to write and print mathematical tables. For a comprehensive discussion on other difference engines, see M. R. Williams 'The difference engines', *Computer Journal*, vol. 19, no. 1 (Feb. 1976), pp. 82-89; and Rudolf Mehmke, *Numerisches Rechnen, Ency. der Math. Wissenschaften* (1901-1904), p. 974.

35] A detailed list of the extensive literature about Babbage would exceed the scope of this study. I direct the interested reader to the detailed and annotated bibliography of Randell (1973), updated in Metropolis (1980), in the third edition of Randell's book (1982) and elsewhere. In my opinion, A. Hyman, *Charles Babbage: Pioneer of the Computer*, Oxford: Oxford University Press (1982), provides the most reliable account on Babbage's work.

36] C. W. Merrifield, 'Report of a committee appointed to consider the advisability and to estimate the expense of constructing Mr. Babbage's Analytical Machine', *The Origins of Digital Computers: Selected Papers* (1973), pp. 53-63. Reprinted in full in Randell (1973), pp. 53-63. What is most fascinating in this report, in addition to its account on the analytical engine itself, is the part that refers to 'the General Principles of Calculating Engine':

> 'The application of arithmetic to calculating machines differs from ordinary clockwork, and from geometrical construction, in that it is essentially discontinuous .... This necessity of jumping discontinuously from one figure to another is the fundamental distinction between calculating and numbering machines on the one hand, and millwork or clockwork on the other. A parallel distinction is found in pure mathematics, between the theory of numbers on one hand and the doctrine of continuous variation, of which the Differential Calculus is the type, on the other. A calculating machine may exist in either case. The common slide-rule is, in fact, a very powerful calculating machine in which the continuous process is used, and the Planimeter is another.... The primary movement of the calculating engines is the "Discontinuous Train"... B is a follower, an ordinary spur wheel with (say) 10 teeth; A is its driver, and this has only a single tooth. With suitable proportion of parts, the single tooth of A only moves B for a whole revolution of A; for it gears with B by means of this single tooth. ... All the other machinery of calculating engines leads up to and makes use of this ... as its means of dealing with units of whatever decimal rank... The primary operation of calculation is counting: the secondary operation is addition, with its counterpart, subtraction... In all the calculating machines at present known, including Mr. Babbage's analytical engine, multiplication is really effected by repeated addition.' Randell (1982), pp. 55-58.

37] Kathleen and Andrew Booth, *Automatic Digital Calculators*, London: Butterworths Scientific Pub., 2nd Ed. (1956), pp. 8-10; H. P. Babbage, 'Babbage Analytical Engine', *Monthly Notices of the Royal Astronomical Society*, vol. 70 (1910), pp. 517-526 and 646, reprinted in full in Randell (1973), pp. 66-69.

After the demise of Babbage (1871), his son Henry carried on his work on the analytical engine and completed the assembly of part of the 'Mill'—the processor and the printing mechanism—with which he demonstrated the working of anticipating carriage. He later built a second mill and demonstrated it with success in 1910, at a meeting of the Royal Astronomical Society. As Randell says (1982, p. 15), 'the saga of Babbage's Analytical Engine came to an end'. No sooner is this said, however, then—and I must pointedly disagree—Randell claims: 'although its fame lingered on and inspired several other people to attempt what Babbage had failed to achieve'. A few lines further on, on the same page (Randell 1982, p. 15) he says exactly the opposite: '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 of this machine were so different from Babbage's designs that there is little reason to doubt Ludgate's claim that he had done his early work in ignorance of Babbage's efforts.

Randell proceeds by cataloguing at least a representative sample of ranks of Babbage's inspired followers, beginning with Leonardo Torres y Quevedo (1852-1936) in Spain (1914, 1920 and 1922), Louis Couffignal in France (1933 and 1938), William Phillips (1936) and Leslie J. Comrie in the UK, and finally Vannevar Bush (1936) and Howard Aiken in the USA (1937). Randell (1982) ends his introduction to Chapter II, Analytical Engines, with the following words: 'With Couffignal's pre-war plans, the line of direct succession to Babbage's Analytical Engine seems to have come to an end'. However, he unthinkingly adds,

> 'Most of the wartime computer projects were apparently carried out in ignorance of the extent to which many of the problems that to be dealt with had been considered and often solved by Babbage one hundred years earlier ... However, in some cases there is clear evidence that knowledge of Babbage's work was an influence on war time pioneers, in particular Howard Aiken ... and various other influential people, including L. J. Comrie, were also well aware of his dream.'

To put it bluntly, the 'clear evidence' that Randell refers to does not exist. Even the story of Aiken's having solved the problem of Babbage's dream is a part of a hindsight myth. This is one of my major claims here: there is no linear tradition, connection, lingering or inspiration between Babbage's efforts and what resulted in the period 1935-1945. What puzzles me most is the ability of scholars to write, sometimes in the same sentence, a claim and then causally state its negation. But the psychology of this exceeds the scope of the present study.

38] Konrad Zuse constructed the Z1 in his parents' living room out of metal sheets cut into strips; these were cut by fellow students with ordinary tools such as saws. But he constructed his device naturally with binary technology and binary notation that was, to my mind, inferior to that used by Babbage.

39] Hyman (1982), pp. 167, 170, 209, and 246. Hyman is of the following opinion. 'The claim that Babbage failed in the construction of the machine is not correct, as Babbage never intended to construct it and he was carrying out trials to prepare a plan and specification, which will prove that it is feasible to construct such a machine if someone decides to do so' (p. 209). Hyman's claim deserves a deeper inquiry, though many scholars will reject it out of hand. Further on, Hyman argues that there is a misunderstanding concerning Babbage's work. Previously, the supposition was that Babbage had designed only a single analytical engine; it turns out that it was a series of machines. 'Until 1976 there was not a published list of the various designs of the analytical engine' (p. 255).

Hyman says that for years Babbage followed the development of the electric light by electric arcs, electro-magnets, and other applications of electricity for the household, but in his opinion the technology lacked the integrity and unity suitable for his own work (pp. 225-226). When Babbage had seen some of Wheatstone's instruments he considered the adaptation of the electro-mechanical switch in lieu of the mechanical switching techniques. In his notebook from May 18, 1838 he wrote,

> 'Yesterday saw Wheatstone's model for telegraph and his drawings for multi-engine... it would require 17 times as many units of electrical time as it does of engine time—but the unit of electrical must really be limited by unit of escapement time' (p. 227).

Hyman (1982, p. 167) also claims that had Babbage adopted binary notation instead of decimal, it would have caused inefficient use of his storage space. This claim is unsupported. The storage area needed for binary notation information is more efficient by 3.34% than the storage area required for decimal notation numerical data of the same order. For example, in a standard punch card, there are 80 columns, each with 10 lines representing the digits 0 to 9. For instance, the store the number 1009 in decimal notation requires four columns: placing the digit 1 in the first column; the digit 0 in the second; the digit 0 in the third; and the digit 9 in the fourth. In binary notation, the whole number 1009 takes up only a single column. The number 1009 is represented in the binary notation as 1111110000, to punch on a single column with six holes on the lines from one to six. Thus, decimal notation requires one column for a single digit every time, while binary notation requires one column to represent a whole number.

Babbage took part in the congress of Berlin on September 18, 1828, in which Gauss and Ørsted participated as well; see Hyman (1982), pp. 73-80, 167, 172, 179, and 184. Babbage should thus have been familiar at least with the possibilities of binary technology and with its advantages. In an interview with me on September 29, 1986, Professor M. V. Wilkes argued against this assessment. He said that Babbage was right in picking decimal notation as it made it easier to construct a machine. I sharply disagree. My evidenced is Babbage's failure. Wilkes is one of the few who has prepared a thorough, comprehensive research on Babbage. He considered him a 'pioneer' of the modern computer. This historiographical trend is exemplified in a Wilkes lecture, 'Babbage as Computer Pioneer' in a *Report of Proc. Babbage Memorial Meeting, London, Oct. 18, 1971*, British Computer Society, London (1971).

Randell (1971), p. 317, seemingly explains Babbage's failure to construct the Analytical Engine: 'It is, in retrospect, clear that the complete Analytical Engine was far ahead of the technology of the time…'

40] Georg Schuetz was a book publisher, with no technical education; he constructed his prototype with his son Edward, who was a qualified engineer. See Uta C. Merzbach, *Georg Scheutz and the First Printing Calculator*, Washington, DC:

Smithsonian Institution Press, (1977). She was the curator of the Smithsonian Institution's calculating devices collection. This is her account of the development of Scheutz's difference engine and its acquisition; see *Smithsonian Studies in History and Technology*, no. 36. A more recent and more updated account is by Michael Lindgren, *Glory and Failure: The Difference Engines of Johann Müller, Charles Babbage and George and Edvard Scheutz* (1987).

41] M. R. Williams, (1976), pp. 85-86. See also M. Lindgren and S. Lindqvist, 'Scheutz's First Difference Engine Rediscovered', *Technology and Culture*, vol. 23, no. 2 (April 1982), pp. 207-213. This is an excellent paper. It presents the rediscovery and the reactivation of Scheutz's prototype model of the difference engine in the cellars of the Stockholm Museum.

42] D. Lardner, 'Babbage's Calculating Engines', *Edinburgh Review* 120 (July 1834); reprinted in Morrison and Morrison (1961).

43] G. B. Grant, 'On a New Difference Engine', *American Journal of Science* (3rd Ser.), vol. 1, no. 8 (August 1871), pp. 113-118. Here is a concise but fairly detailed account of the mechanism of Grant's small prototype model of his difference machine that he was using in the design for a full capacity engine. See Randell (1973), p. 420; as well as G. B. Grant, 'A new Calculating Machine', *American Journal of Science* (3rd Ser.), vol. 4, no. 8 (1874), pp. 277-284. See also M. R. Williams (1976), p. 87.

44] Randell (1971), pp. 317-318; M. R. Williams (1976), p. 87.

45] Comrie refers to this in many places. Suffice to cite two of them: L. J. Comrie, 'The Application of Commercial Calculating Machines to Scientific Computing', *MTAC*, vol. 12, no. 16 (Oct. 1946), pp. 149-159; and Phillips (1936), reprinted in Randell (1973), p. 304. An account on the application of an accounting machine by means of the difference method proposed by von Neumann while he was visiting the UK at the beginning of 1943 is present in J. Todd, 'John von Neumann and the National Accounting Machine', *Siam Review*, vol. 16, no. 4 (Oct. 1974), pp. 526-530.

46] See note 39 above. There is an extensive literature on this, for example, in the bibliography of Randell (1980). While studying Babbage's notebooks in the library of the London Science Museum, I surmised that Babbage's ideas had not yet crystallized, that he had focused on such challenges as the solution of technical problems concerning the passage of carry and so forth. Others, such as Ada Lovelace and Luigi Federico Menabrea, have offered commentaries and interpretations, correct or erroneous, highlighting and illuminating the hidden potential of this device. Sometimes it resembles the fairy tale of Hans Christian Andersen, 'The Emperor's New Clothes': those who are not capable of seeing the qualities of this machine are doomed to be considered stupid, since reputed scholars have already adopted Babbage as a 'computer pioneer' and the standard bearer of the 'computer revolution'. But we have already expounded on the shattering refutation of this myth that Aiken so dearly cherished. Today such myths persist for very similar reasons to those of Aiken, Professor Wilkes Hyman and others. From discussions I held with Doron Swade of the London Science Museum, who was in charge of the calculating means collection, I learned that they intend to reconstruct Babbage's second difference engine. P. E. Ludgate, 'Automatic Calculating Machine', in Horsburgh (1914), pp. 124-127, has an interesting description of the properties of the analytical engine. It opens with a definition of 'automatic calculating machine':

> 'Automatic calculating machines being actuated, if necessary by uniform motive power, and supplied with numbers on which to operate, will compute correct results without requiring any further attention... It must be admitted, that the true automatic calculating machine belongs to a possible rather than actual class; for, though several were designed and a few constructed, the writer is not aware of any machine in use at present time that can determine numerical values of complicated formulae without the assistance of an operator.' (Ibid., p. 124)

This article also refers to Babbage's and Scheutz's difference engines. Yet his interest is mainly in Babbage's analytical engine:

> 'This engine was to be capable of evaluating any algebraic formula, of which a numerical solution is possible, for any given values of the variables.' (Ibid.)

Ludgate had earlier referred to Babbage's analytical engine in Ludgate, 'On the Proposed Analytical Machine', *Scientific Proc. of the Royal Dublin Society*, vol. 12, no. 9 (1909), pp. 77-79; reprinted in Randell (1973), pp. 71-85, as well as in Randell (1971), pp. 320-325. Ludgate writes there that Babbage's analytical engine had

> 'shown to be at least a theoretical possibility... Since Babbage's time his analytical engine seems to have been forgotten; and it is probable that no living person understands the details of its mechanism...'

47] Ludgate (1909), reprinted in full in Randell (1971), pp. 320-325 and in Randell (1973), pp. 71-85. See also a review on it in C. V. Boys, 'A New Analytical Engine', *Nature*, vol. 81, no. 2070 (1 July 1909), pp. 14-14; reprinted in Randell (1971), pp. 325-326.

48] This is known today as Binary-Coded Decimal Notation (CBD), meaning the numerical representation is by means of the decimal base, while the technology applied for its representation employs binary means.

49] J. M. Pullan, in *The History of the Abacus* (1968), says that the English word 'number' and its French equivalent *'nombre'* are derived from the Latin *'numerus'*. The words 'add', 'subtract', 'multiply' and 'divide' are all of Latin origin.

50] In the 1930s, J. W. Bryce (1880-1949), the famous engineer at IBM, developed a punch-machine for multiplication. Subsequently, IBM developed for the calculating laboratory of Columbia University calculating mechanical apparats of this kind. By the 1880s, Hollerith had developed an adder component for the tabulator, based on an electro-magnetic version of the Leibniz stepped reckoner. See also Randell (1982), pp. 127-131.

51] L. E. Truesdell, 'Herman Hollerith: Data Processing Pioneer', Master's Thesis, Drexel Institute of Technology (1968), pp. 30-31: 'There ought to be some mechanical way of doing this job. Something of the principle of the Jacquard loom whereby holes in a card regulate the pattern to be woven'. Billings, in charge of the US Census Office, is reported to have said this to Hollerith while he was visiting the hall where the statistical data of the 1880 census were being processed. An extensive bibliography on Hollerith and punch and tabulating equipment is found in Randell (1973, 1982). For example: H. Hollerith, 'An Electric Tabulating System', *School of Mines Quarterly Columbia University*, vol. 10, no. 3 (April 1889), pp. 238-255; extract reprinted in Randell (1973), pp. 129-139. The article giving an account of Hollerith's equipment that served his PhD dissertation at Columbia University.

52] N. S. Dodge, 'Charles Babbage', *Smithsonian Annual Report* (1873), pp. 162-197.

53] Randell (1982), pp. 127-131.

54] See the unpublished PhD dissertation of W. Jensen, *'Hilfsgeräte der Kryptographie'* (1952), submitted to the *Technische Universität München* but later withdrawn. It gives a personal account of a person who, during World War II in Germany was in charge of the development of special purpose devices for cryptographic purposes that use photo electrical tape readers and electro-magnetic relays. A profound statistical analysis of German language properties is also given there, in particular the relative frequency of the single and pairs of letters of the alphabet in the German language. On encoding and decoding, see also A. Cave Brown (1975); Hodges (1983), R. Levin (1978) and F. W. Winterbotham (1974).

55] See the extensive bibliography and basic articles on analog calculating devices at MIT and other places in E. C. Berkeley, *Giant Brains or Machines that Think*, NY: John Wiley (1949), pp. 239-245. See also Randell (1973, 1982).

Another branch of the analog calculating devices is the analyzer or the harmonic synthesizer. This type of device was intended for the study of wave motions related to mathematical and physical functions. The term 'analyzer' refers to a device or machine designed for the analysis and solution of algebraic problems. This term was adopted particularly in conjunction with analog devices, so that in many instances 'analyzer' is also synonymous with 'analog'. The adjective 'differential' in the term 'differential analyzer' refers to the objective of the device, in that it was adapted deliberately for solving differential equations.

The third group of these analog calculating devices is that of the net analyzer, designed in order to solve problems related to communication and electric power networks. For example, if an electric company with a power network system comprising thousands of consumers' electric power feeding lines encountered a malfunction or an excessive load on a particular line, it needs to know in advance how such conditions will affect the overall system. This preplanned reduced scale simulator or model was intended to solve two kinds of problems: problems with constant states and problems with changing states. It is possible, for example, to cause an overload on a certain line and see at once, by means of indicators or measuring instruments, what the reaction and the effect of the new state will be.

Analog calculating devices of an additional type were those aimed to solve a variety of algebraic linear problems, such as a computing device for the solution of large systems of linear algebraic equations for up to thirty equations with thirty unknowns.

56] J. E. Tomayko, 'Helmut Hoelzer's fully electronic analog computer', *Annals of the History of Computing*, 7.3 (1985), pp. 227-240.

57] Horsburgh (1914), pp. 181-277.

58] J. C. Maxwell, 'Description of a New Form of the Planimeter, an Instrument for Measuring the Areas of a Plane Figures Drawn on Paper', *The Scientific Papers of J. C. Maxwell*, NY: Dover Edition, (1965), pp. 230-232.

59] V. Bush, 'The Differential Analyzer, a New Machine for Solving Differential Equations', *Journal of the Franklin Institute*, vol. 212 (1931), pp. 447-488.

60] Wilfried De Beauclair, *Rechnen mit Maschinen. Eine Bildgeschichte der Rechentechnik*, Springer-Verlag (1986), p. 339.

61] *Ibid*., p. 386.

62] De Beauclair (1986), p. 339.

63] F. Cajori, *A History of the Logarithmic Slide Rule and Allied Instruments* (1909), p. 61.

64] *Ibid*., p. 42.

65] *Ibid*., p. 51.

66] *Ibid*.

67] Horsburgh (1920), p. 44.

68] *Ibid*., p. 45.

69] Mauchly's Papers Collection at Van Pelt Library, University of Pennsylvania, Box 8.

Chapter Two

1] E. W. Phillips (1936) in Randell (1973), pp. 293-296.

2] J. Needham, *Science and Civilization in China Vol. II*, Cambridge: Cambridge University Press (1958), pp. 340-345.

3] M. Gardner, 'Book of Wisdom Hexagrams', *Scientific American*, vol. 230 (Jan. 1974), pp. 108-113. Also see note 2 above, Needham (1958), pp. 341-342.

4] W. Leibniz, Philosophical Writings, in G. H. R. Parkinson (ed.) (1973), pp. 1-3.

5] Ibn Al-Razzaz Al-Jazzari, *The Book of Knowledge of Ingenious Mechanical Devices*, D. R. Hill (ed.), Reidel Dordrecht (trans.) (1974). describes a large number of ingenious, sophisticated and complex mechanical automata integrated on sequential pegged drums. Most of these apparatuses are driven by water wheels. These automata independently control the movement of figures or bodies. Some of its sketches and replicas are exhibited at the London Science Museum.

6] A. Buchner, *Mechanical Musical Instruments*, London: Batchworth Press (1950); Q. David Bowers, *Encyclopedia of Automatic Musical Instruments: 1750-1940*, NY: Vestal Press (1972).

7] *Britannica*, 1974 edition, vol. 18, item 'Telegraph', p. 67.

8] *Ibid.*

9] *Ibid.*

10] G. W. Leibniz, *De Progressione Dyadica, Pars 1, Niedersächsische Landesbibliothek,* Hanover. This is a manuscript of March 15, 1679 found in the Leibniz Hanover Collection. For the Latin original source and its German translation see his *Rechnung mit Null und Eins*, Berlin, Siemens-Aktiengesellschaft (1966) pp. 42-47. It also has an account on binary-notation arithmetic, inclusive of a short discourse on the feasibility of designing a binary mechanical calculating device utilizing moving metal balls to represent binary digits. See also Randell (1973), p. 425. Gardner suggests (1958, p. 36) that, following Ramon Lull (1232-1315), Leibniz 1666 *Dissertatio De Arte Combinatoria* proposes to apply algebra to any sort of knowledge, including ethics and metaphysics, within one deductive framework: 'In case dispute arises, there will be no need to argue between two philosophers rather as between two accountants. Because, it will suffice to take two pencils in their hands, seat in their chairs and say one to the other, (with a friend as a witness, if they desire so) let us calculate'. See also the English translation of Leibniz's papers in Leroy E. Loemker, ed., *G. W. Leibniz, Philosophical Papers and Letters*, University of Chicago Press, vol. 2 (1956), p. 1067.

11] C. Babbage, 'On the Mathematical Powers of the Calculating Machine', unpublished manuscript (Dec. 1837), Oxford: Buxton MS7, Museum of the History of Science. Reprinted in full in Randell (1973), pp. 17-52.

12] J. H. Müller and Ralf Bulow (1989).

13] A. Brlow, A History and Principles of Weaving by Hand and Power, London: Sampson Low, Marston, Searle, & Rivington (1878).

14] F. Kreindl, '*Jacquards Prinzip bereits 200 Jahre alt?*' *Sonderdruck aus Melliand Textilberichte* 2 (1935), pp. 1-2. This special collection gives an account and photographs of a draw-loom incorporating an imitation of the pegged cylinder mechanism, *Broselmaschine*, developed by a member of the Ortner family in upper Austria in or before 1940. It is stated there that the machine is exhibited at the *Heimatsmuseum* in Haslach, Upper Austria. On this see also H. Zemanek, 'Central European Prehistory of Computing' in Metropolis (1980), p. 589 *ff*. A more detailed description is found in Adolf Adam, *Vom himmlischen Uhrwerk zur statistischen Fabrik. 600 Jahre Entdeckungsreise in das Neuland österreichischer Statistik und Datenverarbeitung*, Vienna (1973), p. 139. Adam found in a weaving museum in Upper Austria a programmable process constructed and completed by 1740. Adam has an illustrative survey of astronomical instruments, 'celestial clockery', up until the introduction of Hollerith's punching and tabulating equipment in Austria. He also has a detailed description of Schickard's 'computer clock' and automatic draw looms. See also C. Ballot, *L'Introduction du Machinisme dans l'Industrie Francaise*, O. Marquant, Lille (1923); P. Eymard, *'Historique duMetier Jacquard'*, *Annals des Sciences Physique et Naturells, Societe d'Agriculture, d'Histoire Naturelle, et des Arts Utiles de Lyon*, 3rd Series 7 (1863), pp. 34-56; A. P. Usher, *A History of Mechanical Inventions*, 2nd Rev. Ed., Harvard University Press (1954).

15] *Britannica*, 1974 edition, vol. 18, Art. 'Telegraph', p. 67.

16] The given account is not accurate: the Harvard Mark I and ENIAC have traces of imitation calculating wheels they replace these wheels with electro-magnets and vacuum tubes. The name 'Calculating Clock' appears in Schickard's letter to Kepler.

17] In 1923, Bernard Weiner (born of Jewish origin in Lithuania in 1891; perished in the Holocaust in 1942) obtained a patent, first in Czechoslovakia and later in Britain, for an 'Electric Calculating Machine and Typewriter'. He constructed that device from electro-magnetic relays. The patent application says that in this device's 'programs' were determined permanently for the execution of the primary mathematical operations and trigonometric functions. See also: J. Kalir, 'An Invention that might have Accelerated the Development of Mathematical Machines', *Technical Digest*, vol. 5, no. 5 (1963), pp. 39-41; R. R. M. Mallock, 'An Electrical Calculating Machine', *Proc. Royal Society of London*, Series A, vol. 140 (1933), pp. 457-483.

In Paris in 1920, the famous Spanish inventor Leonardo Torres y Quevedo exhibited an electro-mechanical calculating device (with electrical relays) activated by a typewriter. He indicates that it is possible to connect several typewriters to that calculating machine. Another famous designer and constructor of calculating machines, the German C. H. Hamann, published privately, circa 1932, a pamphlet titled *Über Elektrische Rechenmaschinen* (on electrical calculating machines). It describes electro-mechanical calculating devices, in particular multipliers. It included a device for solving sets of linear equations, with data sets from paper tape. By 1934, the Frenchman R. L. A. Valtat received a patent in Germany for a binary calculating device. His *Calcul Mécanique: Machine à calculer fondée sur l'emploi de la numération binaire (1936)* has a brief description of a proposed calculating machine that translates decimal input into binary before running any calculations. He also points out that binary digits could be recorded by mechanical or electrical means. This is followed by a comment by d'Ocagne, stating that he knew of no previous proposal for a binary machine.

18] D. H. Lehmer, 'A History of the Sieve process', in Metropolis (1980), pp. 445-456.

19] Apokin and Maistrov (1974) in Randell (1982), p. 433.

20] Charles Eryl Wynn-Williams, 'A Thyratron "Scale of Two" Automatic Counter', *Proc. London Royal Society*, ser. A, vol. 136 (1931), pp. 312-32; see also by the same author, 'The use of thyratrons for high speed automatic counting of physical phenomena', *Proceedings of the Royal Society,* ser. A. vol. 132, no. A819 (July 2, 1931), pp. 295-310 and his 'The Scale of Two Counter', *The Year Book of the Physical Society* (1957), pp. 56-60. B. O. Williams (1984, p. 255) lists many examples of patents of electronic, binary counting and calculating means applied between May 1940 and January 1944. See also Randell (1982), p. 433; I. A. Apokin and L. E. Maistrov, *Resvitte Vyichislitelnyich Mashin*, Moscow, *Nauka* (1974). In

Chapter 4 of *The Birth of Electronic Computing*, names Mikhail Aleksandrovich Bonch-Bruevich as having invented an electronic trigger circuit in 1918. There were many more additional designs of counters in the USA and other places during the period 1935-1945, which exceed the scope of this study.

21] See note 16 above.

22] This is quite surprising, since counting is a sequential process of successively adding or subtracting at a defined interval of munerical values. This method was used at the Laboratory of Astronomical Calculations at Columbia University, the Statistical Laboratory founded by Benjamin Wood in 1926. He utilized the standard IBM commercial equipment. The *New York World* daily of March 1, 1920, reports on a calculating device constructed at Columbia University, the computing power capability of which exceeded that of a hundred mathematicians. Even then, IBM performed certain adaptations and changes in its equipment for Wood's needs. Likewise, in the then Iowa State College (later Iowa State University), Henry Wallace established the Statistical Mathematical Service, the first of its kind in the USA, also using IBM equipment.

23] H. J. Dreyer and A. Walther, *'Der Rechenautomat I. P. M. Entwicklung: Instrumente in Deutschland 1939 bis 1945'*, *Bericht A3*, Darmstadt; *Inst. für Praktische Mathematik, Technische Hochschule* (August 19. 1946), pp. 11-15. English translation in Randell (1973), pp. 151-153.

24] According to Goldstine (1972), at the Ballistic Research Laboratories (BRL), Aberdeen, standard IBM punch equipment was introduced by 1940 for ballistic calculations. By 1944, two multipliers especially designed by IBM were installed. Their success led other government agencies to order fifteen additional such machines; *ibid.*, pp. 129-130. Goldstine makes reference here, it seems to me, to the devices described by W. J. Eckert in 'The IBM Pluggable Sequence Relay Calculator', *MTAC*, vol. 3, no. 3 (July 1948), pp. 149-161. Two such machines were installed in Aberdeen in December 1944. They were returned to the factory in November 1945 to increase their capacity for data input and to make other improvements. Three of the improved machines were installed at the Dahlgren Proving Ground VA, and two additional ones were delivered to Columbia University. These machines read data from punch cards, performed a sequence of calculations by a network of relays, and produced a hard copy of their output on punch cards. Moreover, the machine performed the arithmetical operations of addition, subtraction, division, multiplication and extraction of square roots.

25] 'De Forest Electrical Computers', *MTAC*, vol. 2, no. 15 (July 1943), p. 143, reports that he had hitherto published an article in response to 'A Wheatstone Bridge for Solving Numerical Equations', vol. 3 (1897), pp. 200-206, that reports on a new way to solve equations by means of electricity. The equations were set on a device in which the deduction of the result was obtained by adjusting resistances at the Wheatstone bridge, by sliding potentiometers creating equilibration in the Wheatstone bridge system. De Forest also noted the possibility of automatically obtaining the state of equilibration in the system. In his opinion, it was possible to construct a Galvanometer of the relay type that would electrically regulate a given apparatus that would remain in flux until it arrived at a state of equilibrium. Although it was not the first account of such an idea, it is one of the very earliest descriptions of an electrical central regulating apparatus or a self-centering servo-mechanism intended for calculating devices serving as a primary and basic unit in several military designs, in analog calculating devices surfacing during World War II, including an electrical control for anti-aircraft artillery. De Forest was skeptical as to his own ability to realize his idea.

26] Randell (1973), pp. 107-112; Torres' article (Sep.-Oct. 1920), *'Arithmometre Electromechanique'*.

27] Randell (1982), pp. 121-125; from L. Couffignal's PhD dissertation (1938), 'Scheme of Assembly of a Machine Suitable for the Calculations of Celestial Mechanics', p. 125:

> '...the connections between different parts of the machine are all electrical; the arrangement of the latter does not clash with any of the geometric or kinematic constraints which one meets with in a purely mechanical device where all movements are caused or guided by physical contact; the number of each different type of component is therefore theoretically unlimited and in practice very high.' (*ibid.*, p. 125).

28] W. Mays, 'First Circuit for an Electric Logic Machine', *Science*, vol. 118 (4 Sep. 1953), pp. 281-282; an additional account is in A. W. Burks, 'Book Review: *The New Elements of Mathematics* by Charles S. Peirce', ed. Carolyn Eisele (1976) in *Bulletin of the American Mathematical Society*, Vol. 8, No. 5 (Sep. 1978), pp. 913-917. Burks claims there that it was Peirce who had encouraged Marquand to invent and construct a mechanical logic-machine with Boolean logic. In a letter of 1886, Peirce proposed to Marquand to utilize relays in his logic machine, showing it possible to obtain disjunctions and conjunctions by the use of relays and to 'construct a machine for particularly difficult mathematical problems'. After this letter, Marquand turned to draw the sketches of the logic machine that uses relays. Burks adds that Peirce tried to construct Babbage's Analytical Engine with the use of electro-magnets: 'I think that when Peirce wrote his 1886 letter he saw that a relay version of Babbage's machine could be built and that it would work' (*ibid.* p. 917).

29] Zuse (1962), 'The Outline of a Computer Development from Mechanics to Electronics', reprinted in Randell (1973), pp. 171-186; see p. 175:

> 'The author, too, began his first development on a purely mechanical basis. His object was to develop a mechanical analog for the electrical relay. From this the 'mechanical switching element techniques resulted'.

The Zuse patent application of April 11, 1936—Randell (1973), p. 164—says,

> 'The devices and circuits are assembled for the most part from relays. For this existing electro-magnetic relays can be used, or mechanical coupling and uncoupling devices. Only the circuit diagrams are important the word 'impulse' can mean a physical pressure, an electrical current or something similar'.

30] W. Mackie, *A Noble Breed: The Auckland Club 1874-1974*, Auckland: Wilson and Horton (1975) contains a chapter on G. A. Julius and his Totalistic, first used in

1913, by Auckland Racing Club. It was a mechanical device that provided continuous updated displays of the grand total and the individual totals of bets made on up to thirty horses in a race. See Randell (1982), p. 490.

31] Bernhard Wiener applied for a patent on September 8, 1923, in Czechoslovakia (patent no. 30571) and in the UK (patent 224, 549). In 1924 he applied for an 'Electric Computer and Typewriter' (the English translation is erroneous; see below) or a 'Typewriter-controlled Calculating Machine' built out of relays. See J. Kilt, 'An Invention that might have Accelerated the Development of Mathematical Machines,' *Technological Digest*, vol. 5, no. 5 (May 1963), pp. 39-41. The patent describes a machine using hardware imprinted procedures for basic arithmetic, trigonometric, exponentiation and other operations. Kilt states that a special department was set up in the Czech Republic at the Vítkovice Iron Works, to develop Weiner's idea for the design of a fully automatic computer; the German occupation put an end to this. See Randell (1973), p. 240, note 8 and Randell (1982), p. 482.

A German patent was issued to 'Bernhard Weiner in Prag Dejvice' (Dejvice is a part of Prague), on March 22, 1928, in the German Patent Office in Munich: *'Reichpatentamt Patentschrift Mr. 458481 Klasse 42m Gruppe 14... Elektrishe Rechen-und Schreibmaschine. Patentiert im Deutschen Reich vom 8. November 1923 ab'*. Obviously, the English translation of this is a misleading anachronism: the patent is for an 'Electric calculating and typewriting machine'; the use of the term 'computer' in lieu of 'calculating machine' in the 1960s and 1970 for an instrument designed in the 1920s is misleading.

32] B. O. Williams (1984), pp. 109-120, has a good account on the use of various electro-magnets as calculating means, such as the Strowger and the Crossbar.

33] *Ibid.*

34] Randell (1973), pp. 237 and 127; Anon, 'The Thirsk Totalisator', *The Electrical Review*, vol. 106, no. 2724 (7 Feb. 1930), pp. 268-269. It is an account of a particular mobile totalizator demonstrated at the Thirsk racecourse on January 28, 1930.

35] L. F. Woodruff, 'A System of Electric Remote Control Accounting', *Trans. AIEE*, vol. 57 (Feb. 1938), pp. 78-87. See Randell (1973), p. 440. It is an account of an 'experimental system, installed in a department store, involving terminals connected over telephone lines to a set of tabulators and on-line typewriters.'

36] J. Bernstein, *The Analytical Engine*, NY: Random House (1951), p. 51; also see Martin O. Holoien, *Computers and their Social Impact*, London, NY: John Wiley & Sons (1977), pp. 34-40.

37] Hodges (1983) pp. 136 and 146, mentions Turing's return to England from the USA on July 13, 1938 and the electrical binary multiplier that he brought with him.

38] C. A. Beevers, 'A Machine for Rapid Summation of Fourier Series', *Proc. Physical Society of London*, vol. 51, no. 4 (1939), pp. 660-663.

39] G. R. Stibitz, 'Early Computers', in Metropolis (1980), pp. 479-483; E. Loveday, 'The Relay Computers at Bell Labs', *Datamation* (April and May 1967), pp. 35-44 and 45-49.

40] W. E. Phillips, 'A Note on the History of the Electronic Computer' is an unpublished memo (1963) two pages long, it claims that Phillips began work on the design of the ACE with John Womersley in 1943, and that Womersley had started to design a decimal telephone relay computer in 1937, with the assistance of G. L. Norfolk since 1938. Yet, in a letter to the Editor of the *Sunday Times*, dated Sep. 5, 1965, p. 10, Phillips states that he had been interested in Babbage's Analytical Engine since boyhood and that already in 1934he learned about the Eccles-Jordan and the Wynn-Williams devices and conceived a plan for a binary electronic computer. See also his reply in 'Presentation of Institute Gold Medals to Mr. Wilfred Perks and Mr. William Phillips, 23 Nov. 1964', *J. Inst. of Actuaries*, vol. 91, no. 1 (388), (1965), pp. 19-21; Phillips states there that his 1936 paper rests on a memorandum prepared for the Department of Scientific Research, that the government had insisted on patents being filed, and that references to thermionic valves had been deleted from the paper. He also states there that Womersley had learned of the paper in 1943. On this see Randell (1982), p. 500 and p. 300, note 5that says, 'Phillips did file two patent applications relating to calculating apparatus on 24th December 1935. However, no patents were ever granted and there is no record of the contents of the original applications'.

41] Randell (1973), p. 238.

42] C. H. Hamann, *Über Elektrische Rechenmaschinen*, Neubabelsberg, is a privately printed (*circa* 1932) booklet, 32 pages long, on some electro-mechanical calculating devices. They were multipliers of diverse sorts. It also includes a description of a device for solving sets of linear equations with data input from paper tape. See also Randell (1982), p. 472.

43] Randell (1973), p. 287.

44] See note 40 above regarding Phillips' designs, developments and patents concerning various electro-magnetic and electronic calculating devices. See also Randell (1973), pp. 287-291, with notes 3 and 4.

45] B. O. Williams (1984), pp. 255-257; Randell (1973), p. 291; and B. E. Phelps, 'The Beginnings of Electronic Computation', *Report T. R. 00. 2259*, Poughkeepsie, NY: Systems Development Division IBM (9 Dec. 1971). This is a report on early contributions to computer development that gives fair credit to those pioneers of the formative years of the industry. The emphasis is on the IBM engineering development efforts up until the announcement of the IBM 701.

46] N. Wiener, *Cybernetics: or Control and Communication in the Animal and Machine*, 2nd edition, MIT Press (1961), pp. 3-4. The original document was found recently in the MIT Archive with the working title: 'Memorandum on the Mechanical Solution of Partial Differential Equations', file 556 and 557, Wiener papers box 11.

47] For example in ENIAC, in which there still remained a decimal device operating on electronic decimal counters of vacuum tube rings. According to the doctoral dissertation of B. O. Williams (1984), the idea of electronic rings was 'borrowed' from MIT, where work had been undertaken on the Rapid Arithmetical Machine between 1937 and 1942.

48] C. E. Wynn-Williams, 'Electrical Methods of Counting', *Rep. Prog. Physics* 3 (1937), pp. 239-261 contains a survey of work carried out on electronic counting circuits at that time. Its last part discusses auxiliary devices on relays to control electronic counters, on the conversion from binary notation to decimal notation, and on the output of printed hard copies. This continues his ideas of 1931-1932. There is repetition of passages from his 'The Scale of Two Counter', *Year Book of the Physical Society* (1957), pp. 56-60, that is a report on his work on Thyratron-based counters in the Cavendish Laboratory, and later at Imperial College. He explains how an electronic ring counter was first built in 1930, and how in 1931 a binary counter was capable of recording events occurring at 1/1250 second intervals. By 1935, basic electronic counters had been provided with ancillary equipment, using relays and uniselectors for binary-decimal conversion, timing of runs, and automatic printouts. A second version of his apparatus at Imperial College contained means that allowed operating on it remotely by telephone. 'Finally, just before war broke out, a program device was added, which could control experimental conditions and carry out cycles of pre-arranged runs by remote control of the equipment'. See also Randell (1982), p. 530; and Metropolis (1980), p. 648.

49] William H. Desmond, 'From idol to computer', *Datamation* 16.1: 82 (Jan. 1970), pp. 179-183.

50] An interesting explanation on the transition from the automated loom to the punch card or tape appears in P. & E. Morrison (eds.), Charles Babbage and his Calculating Engines: Selected Writings by Ch. Babbage and Others, Dover Pub (1961), pp. xxxiii-xxxv. This is a section written by the editors that contains some of the history of the punch card. It is a report that in the UK [Edmund Cartwright] in 1787 and in Austria around 1680-1690, looms appeared that apply binary-principle controls. The Austrian Brosel used in 1740 A control apparatus with wooden pegs. For details see F. Kreindl, '*Jacquard Prinzip bereits 200 Jahre alt?*', *Sonderdruck aus Melliand Textilberichte*, Heidelberg 2, pp. 1-2 (8 May 1935). This is a written and illustrated report on a draw-loom incorporating a wooden sequence control mechanism involving small wooden pegs fixed on a length of canvas, somewhat akin to a pegged cylinder mechanism. The author suggests that this '*Broselmaschine*' was invented by a member of the Ortner family of Muhlviertel in Upper Austria in or before 1740 and that the invention was independent of Bouchon and Falcon, Jacquard's precursors. It states that the machine is on exhibit at the *Heimatsmuseum* in Haslach, Upper Austria. See also H. Zemanek, 'Central European Prehistory of Computing', in Metropolis (1980), p. 589; A. Adam, *Von Himmlischen Uhrwerk zur Statistischen Fabrik*, Vienna: H. O. Munk (1973), p. 139; and Randell (1982), pp. 431, 484, and 531. See also note 14 above.

51] For a detailed description of clocks and for the ascription of great importance to them see *Britannica* 9th edition (1876) article 'Clocks'.

52] W. D. Nieven, ed., *The Scientific Papers of J. C. Maxwell*, Vol. II, NY: Dover Pub (1965), pp. 105-120, in particular pp. 105-106:

> 'A governor is a part of a machine by means of which the velocity of the machine is kept uniform, notwithstanding variations in the driving power or resistance .. I propose at present, without entering details of mechanism, to

> direct the attention of engineers and mathematicians to the dynamics theory of such governors'.

53] J. Mills, 'Communication with Electrical Brains', *Bell Tel.* vol. 13 (1934), pp. 47-57 is a description of an automatic exchange capable of assisting telephone subscribers to get in touch.

54] Carpenter and Duran, 'The Other Turing Machine', *Computer Journal* (August 1977), pp. 269-279.

55] W. H. Eccles and F. W. Jordan, 'Trigger Relay Utilizing Three Electrode Thermionic Vacuum Tubes', *The Radio Review*, London, vol. 1 (Dec. 1919), pp. 143-146, Reprinted in Earl E. Swartzlander, Jr., ed., *Computer Design Development: Principal Papers*. Rochelle Park NJ: Hayden Book Coy. (1976).

56] The Strowger handles ten-by-ten matrices and so it is operative in one hundred different states. USA Patent Office: Almon B. Strowger, of Kansas City MO, Automatic Telephone-Exchange. Specifications forming part of Letters Patent No. 447,918, dated March 10, 1891. Application filed March 12, 1889. Serial No. 303,027. (No model.)

57] Phillips (1936) in Randell (1973), pp. 301-304; it contains an extensive bibliography by L. Comrie.

58] Couffignal (1933) in Randell (1973), pp. 141-150.

59] Randell (1982), pp. 147-148.

60] Randell (1982), p. 448.

61] C. E. Shannon, 'A Symbolic Analysis of Relay and Switching Circuits', *Trans. Amer. Inst. Electrical Engineering*, vol. 57 (1938), pp. 713-723; V. Bush, *Operational Circuit Analysis*, NY: John Wiley & Sons, p. 929.

62] V. Bush, 'Instrumental Analysis', *Bulletin of Amer. Math. Soc.*, Vol. 42 (Oct. 1936), pp. 649-669.

Chapter Three

1] Bowden (1953), p. 368.

2] *Ibid.*

3] The autobiography of Zuse appears in two entirely different editions bearing the same title: K. Zuse, *'Der Computer—Main Lebenswerk'*, first edition, *München: Verlag Moderne Industrie* (1970), second edition, *Springer Verlag*, Berlin (1984). They differ in editing and in content.

4] M. Wilkes, 'How Babbage's Dream Came True', *Nature* (16th October 1975), pp. 541-544; and 'Babbage as a Computer Pioneer', in *Report of Proceedings, Babbage Memorial Meeting, London, 18th October 1971*, London: British Computer Society (1971).

5] For example, the International Research Conference on the History of Computing held at the Scientific Research Laboratories, Los Alamos NM, June 10 and 15, 1976.

The papers given there appear in N. Metropolis *et al.*, eds., *A History of Computing in the Twentieth Century*, Cambridge MA: Academic Press (1980).

6] C. Evans, *Pioneers of Computing: An Oral History of Computing*, compiled with the support of the Science Museum and the National Physical Laboratory. This is a series of some twenty recordings, each an hour long. Among the interviewees are Zuse, Eckert, Mauchly and Combes, one of the members of the team that developed the Colossus. Having read the transcripts at the London Science Museum, I deem them very poor resources.

The transcripts of Tropp's project are held at the Smithsonian Institution, Washington, DC. It originated with a contract signed by the American Federation of Information Processing Societies (AFIPS) and the Smithsonian's National Museum of History of Technology in 1967. Isaac Auerbach, Cuthbert Hurd, Walther Carlson, Rudy Winnacker, Robert Multhauf and Bery Finn were joined by Henry S. Tropp in Spring, 1971. The reports provided there are no better resources than those of Evans. A report on the interviews carried out by Tropp is found in H. Tropp, 'The Effervescent years: A retrospective', *IEEE Spectrum*, vol. 12, no. 2 (1974), pp. 70-79. Among the interviewees are Stibitz, Atanasoff, Eckert, Mauchly and von Neumann. There is also discourse on the function of American firms such as IBM and NCR. See also H. S, Tropp, 'The Smithsonian Computer History Project and Some Personal Recollections', in Metropolis (1980), pp. 115-122.

On oral documentation see also W. Aspray and Bruce Bruemmer, 'Oral Histories of Information Processing', *Oral History Association Newsletter*, vol. 8, no. 4 (Fall 1984), p. 2.

7] R. L. A. Valtat obtained a German patent (number 664012) with priority in France for a calculating machine that translates decimal input into binary before performing the calculating operation. Valtat indicated that it was possible to represent binary digits by mechanical means and by electrical means. I obtained a copy courtesy of Dr. Joachim Fisher of the *Deutsches Museum* in Munich.

8] D. Hilbert and W. Ackermann, *'Grundzüge der Theoretischen Logik'*, in *Grundlagen der Mathematischen Wissenschaften, Band* 17, Berlin: Verlag von Julius Springer (1928) and later editions.

9] See Zuse (1984), pp. 30-31, and Ceruzzi (1983), *Reckoners*, p. 15.

10] See Zuse (1984), p. 67. There is an excellent account of how Zuse obtained the picture of Aiken's Mark I.

11] K. Zuse, *Verfahren zur Selbsttätigen Durchführung von Berechnungen mit Hilfe von Rechenmaschinen*. This is Zuse's patent application in Germany. It bears the number Z-23624, dated April 11, 1936. It seems his application was rejected by the court after the War. H. Petzold has provided an excellent discussion of this.

12] Hamann was possibly one of the best known German producers and designers of calculating machines. CH. Hamann, *'Über Electrische Rechenmachinen'* (1932) is 32 page long privately published booklet on electrical calculating machines that discusses various types of calculating devices with electro-magnetic multipliers, including a device for the solution of sets of linear equations, with a data feeding punch tape.

The detailed account of the telephone conversation between Zuse and Panneke is in Zuse (1984), pp. 38-39.

13] F. L. Bauer, H. Wossner, 'The *"Plankalkül"* of Konrad Zuse: A Forerunner of Today's Programming Languages', *Communications of ACM*, vol. 15, no. 7 (July 1972), pp. 678-685 and p. 678

14] Wynn-Williams, 'The use of Thyratrons for High Speed Automatic Counting Physical Phenomena', *Proceedings Royal Society London,* Series A 132 (1931), pp. 295-310.

15] W. H. Eccles and F. W. Jordan, 'A Trigger Relay Utilizing Three-Electrode Thermionic Vacuum Tubes' (1919). As to the oversight of the works of Wynn-Williams and of others, see *F. L. Bauer, 'Helmut Schreyer - Ein pionier des "ElektronischenRechnens"'*, in *Informatik Spektrum* 5 (1982), pp. 186-187.

16] Zuse's biography *'Der Computer - Mein Lebenswerk'* (1984), pp. 34-37. This was the subject-matter of my discussion with Zuse in September 1986.

17] The discussion I held with Stibitz on 17th October 1986 lasted for hours and is on oral record.

18] *Ibid.*

19] *Ibid.*

20] *Ibid.*

21] Mauchly's papers, held at Van Pelt Special Collections, University of Pennsylvania, Box 1, File 2.

22] A letter from the Provost of Johns Hopkins, dated 17th October 1927, asks Mauchly to decide which of the two scholarships he wanted to retain. Van Pelt Special Collections, Box 1, File 2.

23] My information here stems from some twenty boxes of Mauchly's personal documents, held at Van Pelt Special Collections at the University of Pennsylvania. The Moore School of Electrical Engineering of the University of Pennsylvania, has also an additional archive, but its biographical value is very poor. This also applies to the main archive of the university that is even less useful in this context.

24] Mauchly's Papers, Box 1, File 2.

25] William and Elizebeth Friedman, *The Shakespearean Ciphers Examined: An Analysis of Cryptographic Systems used as Evidence that Some Author Other Than William Shakespeare Wrote the Plays Commonly Attributed to Him*, Cambridge: Cambridge University Press (1957).

26] *Ibid.* Mauchly's Papers, Letter of 2 July 1936, Box 1, File 2.

27] Mauchly's Papers, Box 5, File 55.

28] *Ibid.*, Box 6, File 15.

29] *Ibid.*, Box 5, File 7.

30] Mauchly's Papers, Box 6, File 15.

31] *Ibid.*, Box 6, File 15.

32] *Ibid.*

33] K. R. Mauchly, 'Mauchly's Early Years', *Annals of the History of Computing*, vol. 6, no. 2 (April 1984), p. 126.

34] Mauchly's Papers, Box 9B, File 161 (29).

35] *Ibid.*, Box 7, File 1 (86).

36] The Resume-Education and Experience of John W. Mauchly, a copy of which the Van Pelt Special Collections kindly gave me. It is almost evident that it was written by Mauchly himself. It contains seven pages in all. Imprinted at the end of it is 'JWM 4/71'that stands for John William Mauchly, April 1971.

37] *Ibid.*, page 4.

38] Note attached to Mauchly's memo of August 1942, Trial Exhibit 1376; see also next note.

39] Among the documents of the Honeywell vs. Sperry Rand Trial, stored at the Archive of the Charles Babbage Institute, University of Minnesota, Minneapolis, I found documents that shed new light on this issue. My term 'First Draft', relates to a group of documents probably intended to serve as a draft for the remarks of the people at the Moore School involved in the project. They bear the heading: 'Report on an Electronic Diff. * Analyzer, having the date of April 2, 1943'. These documents are court exhibits number 1417, 1427, 1431 and 1432. However, these exhibits may each consist of more than one page and even include appendices that were added later on. The First Draft contains nine pages and Appendix A. I deem this the basic document. Page 9 has a footnote for the opening page heading:

> '*Footnote: The word Diff. * is deliberately abbreviated. Present differential analyzers operate on the basis of integrating continuously, i.e., by differential increments; the electronic analyzer, although it is believed that it would be both speedier and more accurate, would operate using extremely small but finite differences. The abbreviation 'Diff. *' may thus be considered to represent 'difference' rather than 'differential' in the case of the electronic device.'

To my surprise, I found a considerable number of copies of the 1943 Report. The various copies of the Report among the trial record can be usefully classified into three groups:

1. Full and partial copies of the original First Draft: Exhibits 1417, 1427, 1431 and 1432.

2. Copies of the First Draft that had been corrected by hand, in ink: Exhibits 1421 and 1448.

3. A copy of the Final Report: 1440.

The First Draft, April 2, 1943

This document contains two parts and three appendices. Part one comprises four pages including a general introduction that describes the instrument and the labor and the costs involved in its construction. The second part, five-pages long, deals with technical details, definitions and an illustrative example. Appendix A of the report is Mauchly's memorandum of August 1942. Appendices B and C provide examples of solutions of external and internal ballistics problems.

Trial Exhibit 1417 is an incomplete copy of the Draft Report, comprising only nine pages, containing only Parts 1 and 2. At the center of the cover page is 8x14 cm frame with a handwritten note: 'Proposal for ENIAC'. Appendix A is missing as this is an early report. There is a handwritten 'Appendix E' in the following 'Rough Draft Report' folder. It is not clear who added this cover page or when. What is clear from this note is that the writer was aware that this was an early draft. However, the mention of 'Appendix E' may be misleading, as there was no Appendix E in the Draft Report. Quite what the reference to a 'Rough Draft Report' means is unclear, since there is no evidence that any rough drafts had preceded what I have termed the Draft Report.

Trial Exhibits 1427, 1431 and 1432 all have an otherwise blank cover bearing a handwritten note identifying it as 'The basic document (PX) written by GJB [Grist John Brainerd] and submitted personally to Col. Simon', further stating that 'This much sent to Aberdeen April 2, 1943'. However, it is not clear whether this page belonged to the original document; the 'PX' indicates the contrary, assuming that it was written at the same time. The 'PX' code was the Moore School's accounting symbol for ENIAC charges, as 'PY' was for EDVAC (Goldstine 1972, p. 187, note 8). ENIAC contract (Exhibit 1532) was signed on June 2, 1943.

Of all the Trial Exhibits, only Exhibit 1432 contains any of the three appendices listed in its table of contents. Yet even here, Appendix B is missing, and Appendix C bears the title 'Application of the Analyzer to a set of Equations for External Use'. This does not fit with the table of contents whose title for Appendix C is 'Interior Ballistic Equation', and whose text is that of the Appendix C of the Final Report. Similarly, though an Appendix E is attached to the Report, the text of this Appendix is that of Appendix E of the Final Report, though retyped, with its drawings executed more carefully. I therefore conclude that it has been added to Exhibit 1432 perhaps by mistake. Exhibit 1432 seems to me a random gathering together of two kinds of reports: Parts 1 and 2 and Appendix A belong to the First Draft, while Appendices C and E have been attached to it perhaps by mistake, and they belong to another version of the Final Report.

The Corrected First Draft.

Exhibits 1421 and 1448 are the First Draft Report, but with handwritten corrections. It contains ten pages in all. The two documents are identical, being photocopies of the same corrected original. They have an otherwise blank cover, bearing the handwritten explanation 'Corrected Copy of 1st rough draft plus additions. ENIAC proposal' (Mauchly?). The corrections appear only in Parts One and Two. Those made to Part One consist of the following: the date is corrected from April 2 to April 8; the word 'Difference' is written on the title of the report; there is a request that the typing of the title be double-spaced; whenever the word Diff* appears on the First Draft it has been corrected to 'Difference'; the many other corrections are minor.

The Contents listing is altered to indicate the addition of a new Appendix B entitled 'Speed of Operation: Illustrative Arithmetic Problem', and the consequent renaming of the previous Appendix B and Appendix C. A handwritten section is added on a separate page, between pages three and four, dealing with the incorporation of IBM equipment and the implications of this regarding costs, in which the following statement appears: 'an electronic difference analyzer could be built almost entirely of commercially available standard elements about which there is ample information'. The content of the footnote on page four also contains handwritten corrections, including the replacement of the last sentence by: 'it thus is more appropriate to refer to it as a difference analyzer rather than a differential analyzer'.

The Final Report of April 8, 1943

Here only Exhibit 1440 will be discussed. It has a typed cover stamped 'Confidential' and the title 'Report on an Electronic Difference Analyzer'. It identifies no author and no editor. The contents listing of this report has five appendices, as compared to the three in the First Draft and four in its corrected version, all of which are present in the copy labeled Exhibit 1440. The new fifth appendix, Appendix E, is entitled: 'Description of Units Composing Analyzer' and, in consideration of the crudely drawn figures, shows signs of having been prepared in haste. The text of the handwritten page of the Corrected Draft is incorporated, and in Part Two, on page eight, a paragraph is added, entitled '3. Brief Description of the Electronic Analyzer'. In total the Final Report has thirty-eight pages, including the cover.

Finally, from a handwritten page of Exhibit 1446, we learn that the Final Report was distributed as follows: Copy 1 to L. E. Cunningham at Aberdeen; copy 2 to V. Zworykin at RCA; copy 3 to Col. Gillon of the Ordnance Office; and copies 4 and 5 to the Moore School, where Burks received copy 4 on June 21, 1943, and E. Knobeloch received copy 5 on June 23, 1943.

Mauchly's reproduced memorandum appeared in all versions of the Report as Appendix A, 'The use of High Speed Vacuum Tube Devices for Calculating. Reproduction of a Memorandum Privately Circulated in August 1942'. The original memo was discovered twenty years later in the Moore School archives, the reproduction was reconstructed from the stenogram of Mauchly's secretary. Added to the original Mauchly memo from August 1942 is a handwritten note, bearing the title 'Trial Exhibit 1376': 'Read with interest. It is easily conceivable that labor shortage may justify development work on this in the not too far distant future'.

40] Aiken's Papers found at Harvard University, Pusey Library.

41] Components of Babbage's Differential Engine, Parts of Mark I, and Aiken's original proposal are displayed at Aiken's Computational Laboratory, Oxford Street, Harvard.

42] Professor I. B. Cohen found a rare interview conducted by George Chase, an expert on calculating machines at the Monroe firm, with Aiken on April 22, 1937, describing the properties of Aiken's machine and its contribution to mathematics, science and society. Cohen's report on it appears as an introduction to the paper of

G. C. Chase, 'History of Mechanical Computing Machinery', *Annals of the History of Computing*, vol. 2, no. 3 (July 1980), pp. 198-226.

43] H. S. Tropp, 'The Smithsonian Computer History Project and Some Personal Recollections' in Metropolis (1980), pp. 115-122.

44] A letter of September 5, 1940, found among Aiken's papers at Harvard UAV298. 2005. In it Aiken describes his qualifications to the Chairman of NDRC, a BS in Electrical Engineering from the University of Wisconsin and an MA and PhD from Harvard.

45] J. Bernstein, *The Analytical Engine: Computers, Past, Present and Future*, NY: Random House (1963), pp. 50-51.

Professor Cohen told me in our meeting in his office at Harvard on October 16, 1986, that he also knew that Aiken had constructed two machines for the solution of large systems of algebraic equations with many variables before publishing his 1937 proposal. He added that Aiken had a hydraulic analog device (Cohen, 1999, pp. 36*ff*.). Getting Iwen, a physics graduate student, sent Professor Cohen a copy of a biography that offers an account of a relay device that he had received from Bell, although he had not the slightest idea as to its purpose.

From Professor Cohen I learned also that the account given in Bernstein's book rests on interviews he had conducted with Aiken.

46] H. Aiken's 'Proposed Automatic Calculating Machine' was first made public only in 1964. The original proposal does not bear a date. All the known copies today carry the date marked by one of the recipients as November 4, 1937. Considering what is said in footnote 33, it is possible that the true date of this proposal is much earlier, namely, the beginning of 1937.

47] G. C. Chase, 'History of Mechanical Computing Machinery', *Proceedings ACM, Pittsburgh 2-3 May 1952*, pp. 1-28 (see also note 33 above). Reprinted in *Annals of the History of Computing*, vol. 2, no. 3 (July 1980), pp. 198-226.

48] This information I owe to the generosity of Professor Cohen of Harvard, who provided it during our meeting on October 16, 1986. See also J. Bernstein, *The Analytical Engine*, NY: Random House (1963), pp. 51-53.

49] C. Babbage, *Passages from the Life of a Philosopher* (1864); reprinted by Augustus M. Kelley: NY (1969):

> 'If, undeterred by my example, any man shall succeed in constructing an engine embodying in itself the whole of the executive department of mathematical analysis, I have no fear of leaving my reputation in his charge, he alone will be fully able to appreciate the nature of my efforts and the value of their results'.

50] Many scholars have stumbled into the pitfall of Aiken's misinformation. For instance, P. Ceruzzi in his book *Reckoners* (1983), based on his own PhD dissertation. On page 48 there he says 'Aiken felt that Babbage's principles were theoretically sound', then he proceeds on pages 62-63 to add the following:

> 'So Aiken not only acknowledged Babbage as his inspiration for his plans to build a sequence controlled calculator, but he also incorporated some of

> Babbage's very methods into his machine as a way to check its reliability. The link between Babbage and the modern computer age is a complex one. Other computer pioneers from the 1935-1945 era knew Babbage: Zuse in Germany, Bush at MIT, perhaps a few others. But Aiken, and probably only he, consciously saw his own role as one picking up where Babbage had left off a century before... Aiken conceived MARK I as a direct successor of the Analytical Engine, and the Mark I was a general purpose computer. But the spirit of the Difference Engine lived in it as well.'

In my humble opinion these claims are baseless. Comparing the 1937 proposal with the 1946 joint paper of Aiken and Hopper readily shows that the latter is misleading. Hopper describes how, on the first day when she was introduced to Mark I in 1944, she was also already acquainted with the work of Babbage. Aiken had a copy of Babbage's book and over time he recommended each member of his staff to read parts of it. Hopper claims that she was aware of Ada Lovelace until some ten or fifteen years later. (See G. M. Hopper, 'Computer Software' in *Computers and Their Future*, Llandudno: Richard Williams and Partners (1970), pp. 7/3-7/26.)

51] Atanasoff and Brandt, 'Application of Punch Card Equipment to the Analysis of Complex Spectra', *Journal of the Optical Society of America*, vol. 26, no. 2 (February 1936), pp. 83-88. It is a detailed account of the operation of a tabulator by means of an attached homemade cross connecting board, on which numerical values could be set, and not by means of punch cards as was then common.

52] David Gardner, 'The Independent Inventor', *Datamation* (September, 1982), p. 14.

53] J. V. Atanasoff 'Advent of Electronic Digital Computing', *Annals of the History of Computing*, vol. 6, no. 3 (July 1984), p. 238.

54] See Linda R. Runyam, 'A Master of Under-Statement', *Datamation*, vol. 26, no. 5 (May 1980), p. 85.

55] *Ibid.*

56] Atanasoff, 'Computing Machine for the Solution of Large Systems of Linear Algebraic Equations', an internal University of Iowa unpublished memorandum from August 1940. Reprinted in full in Randell (1982), pp. 315-335.

57] J. P. Eckert, *The Beginning and to What End, in Computer and Their Future*, Llandudno: Richard Williams and Partners (1970), pp. 3/4-3/24. Mauchly confessed there his early ignorance of Babbage as well as of Eckert:

> 'We have been asked many times, if we knew of Lovelace, or Babbage, and their work. At that time I did not know of the work. When we started on ENIAC, we did not know of the work of Mark I.'

This passage is also found in Randell (1973), pp. 415-416. It is corroborated by John Grist Brainerd, who was in charge of ENIAC project on behalf of the University of Pennsylvania. A paper by W. van Norman Royce, 'Charles Babbage (1792-1871)', *Journal of Industrial Engineering*, vol. 16, no. 1 (Jan-Feb. 1965), pp. 3-5, drew public attention. Brainerd reviewed it in *Comp. Reviews* 6, No. 5, 284 (1965). He registered there the claim that the development of ENIAC had been in total ignorance of Babbage's work and that

> 'the modern computer is the large scale high speed electronic digital computer which started with ENIAC (1943-46). Babbage's direct influence was nil, and his indirect influence only that reflected in industrial system which included in it a strong electronics industry... Babbage, because of the remoteness of his work (mechanical Vs' electronic, incomplete Vs' complete, unreliability Vs' reliability etc.) is still less the 'father' of modern computers.'

Brainerd concludes with a warning:

> 'A student of the history of technology might well consider whether Babbage—an extremely brilliant and farsighted man—had any influence whatsoever on the development of ENIAC and the start of modern electronic computers. The author, writing for industrial engineers, has simply parroted what is often heard.'

58] Ceruzzi, P. E., *Reckoners: The Prehistory of the Digital Computer, From Relays to the Stored Program Concept, 1935-1945*, Westport, Conn.: Greenwood Press (1983), p. 112.

59] Eckert (1976) in Metropolis (1980), p. 538.

60] The Diff. *: and Difference reports, 2nd and 8th April 1943; see note 30 above.

61] J. V. Atanasoff, 'Advent of the Electronic Digital Computing', *Annals of the History of Computer* (July 1984), p. 241; J. R. Berry, 'Clifford Edward Berry 1918-1963: His Role in Early Computers', *Annals of the History of Computing* (October 1986), pp. 361-369.

62] J. R. Berry (1986), pp. 364-366.

63] On Wynn-Williams' activity before the war, see his 'The Use of Thyratrons for High Speed Automatic Counting of Physical Phenomena', *Proceedings of the Royal Society*, London, A132 (1931), pp. 295-310; 'Electrical Methods of Counting', *Rep. Progr. Phys.* 3 (1937), pp. 239 261; 'The Scale Two Counter', *Yearbook, Physical Society* (1957), p. 56-60. On his activities in the Colossus during World War II (1942-1943), see B. Randell (1976) 'The Colossus', in Metropolis (1980), pp. 49-92, and A. Hodges (1983), pp. 225-256, 262 and 267.

64] Hodges (1983) has a good biographical account on Turing. This biography overemphasizes the homosexual aspects of his life, yet the issue of Turing's involvement in the theoretical and practical development of calculating devices receives adequate treatment. Turing's mother, Sara Turing wrote a biography in 1959 entitled Alan M. Turing, in which the information on his activities during the war is minimal. See also Randell (1976) 'The Colossus', in Metropolis (1980). See *The Alan Turing bibliography, https://www.turing.org.uk/sources/biblio.html* by Andrew Hodges.

65] M. Woodger (1958), p. xx

66] Pamela McCorduck (1979), pp. 66 and 74.

67] See Randell (1976) 'The Colossus', in Metropolis (1980). See also *Colossus: The Secrets of Bletchley Park's Code-breaking Computers*, edited by B. Jack Copeland, Oxford University Press, 2006, 2010, authored by Copeland and seventeen participants (Thomas H. Flowers) in the project. See also https://www.theregister.co.uk/2014/02/06/mi5_still_holds_bletchley_park_secrets/.

68] See a special issue of the *Annals of the History of Computing* (vol. 5, no. 3, July 1983) devoted to the Colossus, including the following papers: Thomas H. Flowers, 'The Design of Colossus', pp. 239-252; Allen W. M. Coombs, 'The Making of Colossus', pp. 253-259; W. W. Chandler, 'The Installation and Maintenance of Colossus', pp. 260 262; and in B. Randell's paper on Colossus (1976), see Endnotes 53 to 55.

69] K. Zuse 'The Outline of a Computer—Development from Mechanics to Electronics', in Randell (1973), pp. 171-186.

Chapter Four

1] Dijkstra (1986), p. 48.

2] In Germany during the 1930s, it was common to make calculations in engineering or for applied mathematics according to a procedure known in German as the *'Rechenplan'*. This was a practical procedure executed according to a parallel double pattern to avoid errors in calculations on paper forms prepared in advance. In 1932 Zuse started talking about mechanizing the controlled sequence of calculations by means of an apparatus capable of moving in two dimensions along the width and length of the paper form, like a plotter, a drafting instrument. This way it would be possible to read data punched into the form in order to execute basic arithmetical operations and to output the tabulated results. His breakthrough came when he decided to generalize the idea by adding a control to this universal paper form. Between 1932 and 1934 he replaced the idea of the punched form with the idea of a two dimensional array. This made it feasible to store numbers, the integration of an addressing mechanism that connected the storage locations and the arithmetical calculating unit and the control-unit that supervised the system by getting instructions from an exposed 35 mm punched photo film. Schreyer was well acquainted with the technology of film and sprockets, having work experience as a movie projectionist.

To begin with, Zuse intended to use these forms to aid the solution of complex calculations, as part of a complicated scheme in which the numerical values designated for calculating multiplication or division were placed one next to the other, while those for adding or subtracting were located one beneath the other. Only then did Zuse realize that one could also direct the apparatus to find the data for the execution of operations without the need of the two dimensional array. Instead, all that he had to do was to indicate the type of instruction, the location of the data to be acted on and manipulated, and the location where the result of a calculation was to be recorded. See also Randell (1973), p. 155; Ceruzzi (1983), pp. 12-25; Williams (1984), pp. 31-32; and Metropolis (1980), pp. 507 and 612.

3] See the section on the analog devices in Chapter 1.

4] In the Bush Analyzers—both that of 1935 and the other on which work finished in 1942 (the Rockefeller)—the accuracy was 0.02% of the total calculation, namely, it had an error tolerance of +/- 0.02%.

5] The program of Bush appeared in his lecture of January 2, 1936, delivered to members of the American Mathematical Society: Bush V., 'Instrumental Analysis', *Bull. of the American Mathematical Society*, vol. 42 (Oct. 1936), pp. 649-669. It is a milestone in the trends of mechanizing calculations in the USA, possibly in other countries too, yet it has no supporting evidence in practice. For this lecture Bush collected diverse sources related to mechanical calculating devices and other artificial means for storing information. He sent a draft copy of his lecture to Norbert Wiener for comments. Wiener hoped then to be on sabbatical for a year in China. He offered a response on the draft and sent his own proposal for constructing a calculating device for the solving of partial differential equations, in which he then showed great interest.

In his lecture, Bush asserted that it was possible to solve very complex problems by means of simple arithmetic operations, if the operations were sufficiently fast and mainly sequential. The emphasis on speed as a factor in the calculations is of great and peculiar interest, since only the designers of electronic calculating devices, such as those of ENIAC and Colossus, had also stressed the importance of high calculation speeds. So speed factors in new qualities and opens new horizons in calculation. Bush noted that Babbage's Difference Engine was a successful model on many counts:

> 'It is time that a numerical machine was constructed for which the sequence of operations might be varied at will to cover a large field of utility, but fully automatic on execution, once the sequence is organized' (op. cit., p. 654).

And, Bush continues,

> 'A numerical process, however complex, would then be reduced to the recording of raw data, and the exact specification by similar record on the desired numerical process, all else being relegated, as it should be, to the machine. Such an arrangement would no doubt be soon worked out if there were sufficient commercial demand. This would be a close approach to Babbage's large conception as far as arithmetical processes are concerned. It would complete, for arithmetic, the consummation which Leibniz visualized for all mathematics.'

Despite this visionary oration, Bush and his disciples at MIT proceeded to construct analog devices, although work stumbled along on a project supported by MIT between 1938 and 1942 on an electronic Rapid Arithmetical Machine that might have followed the Babbage-style vision of Bush. But the project was abandoned in 1942, possibly due to the war, as happened to so many endeavors. However, they did construct the Rockefeller Analyzer, for which funding was gathered between 1937 and 1942. This device incorporated a punched paper tape control-unit that provided it with some multi-purpose capacities.

6] K. Zuse, *Verfahren zur Selbsttätigen Durchführung von Berechnungen mit Hilfe von Rechenmaschinen.* German patent application Z23624 from April 11, 1936. Randell (1982), pp. 163-170 contains excerpts inaccurately translated.

7] This account is in Zuse (1962), partly also in Randell (1973), pp. 177-186, as well as in Friedrich Bauer (1976), Metropolis (1980), pp. 504-524 and 611-627; and Zuse (1976). A successful account on Zuse appears in Ceruzzi (1983), pp.10-42 and in his PhD dissertation (1980). For details, see Zuse's biography (1984), p. 15.

8] See note 1 above.

9] For a detailed account on this event, see Zuse (1976) in Metropolis (1980), p. 612.

10] For details see F. L. Bauer (1976) in Metropolis (1980), pp. 507-513.

11] The construction of the mechanical Z1 model was completed in 1938. The work on the electro-magnetic Z2 model began in 1937 and was completed by 1939. Due to his general and abstract approach in design, as exhibited in his patent application (see note 5 above), in 1937 Zuse began, together with Schreyer, to study the electronic circuit of vacuum tubes and neon filled tubes. Schreyer constructed a pilot model of an electronic adder that he exhibited in Berlin by 1938. In 1944, Zuse and Schreyer designed an electronic 'computer' that was supposed to have two thousand vacuum tubes; the German research authorities rejected it offhand.

12] There are many references to the Z3. The most reliable are those of Zuse (1962) in Randell (1973), pp. 172-179; Bauer (1976) in Metropolis (1980), pp. 512-513; W. H. Desmond and K. J. Berkling, 'The Zuse 3', *Datamation*, vol. 12 (Sep. 1966), pp. 30-31; and naturally Zuse's biography, *Der Computer Mein Lebenswerk*, Springer Verlag (1984).

13] See note 10 above; Zuse (1962) in Randell (1973), p. 178; and Bauer (1976) in Metropolis (1980), p. 513.

14] See P. C. Lyndon, 'The Zuse Computer', *Math. Tab. and other Aids to Computation* (*MTAC*), vol. 2, no. 20 (1947), pp. 355-359.

15] See note 11 above; W. H. Desmond (1966).

16] The reference is to the S1 and S2 models. See Zuse (1962) in Randell (1982), p. 185; Zuse (1984), pp. 62 and 95; Zuse (1976) in Metropolis (1980), p. 614 and in particular pp. 617-618; Desmond (1966), p. 31; Lyndon (1947) remark 1 there and Ceruzzi (1983), p. 38.

17] Zuse (1984), p. 14.

18] Zuse (1967) in Metropolis (1980), pp. 611-612:

> 'So in Germany when I started in 1934 nobody knew him (Babbage) or his work.. also later as an engineer in aircraft industry I became aware of the tremendous number of monotonous calculations necessary for the design of static and aerodynamic structures. Therefore, I decided to design and construct 4 calculating machines suited to solve these problems automatically. The work proceeded almost parallel to, but quite independently of, the developments in the United States by Stibitz, Aiken, Eckert, Mauchly and others.'

19] See Hodges (1983), pp. 124, 152, 216 and remark * on p. 253. In any case, Zuse's work began before the publication of Turing's paper in November 1936. Zuse writes in his biography (1984), *Der Computer MeinLebenswerk*, pp. 73 and 76, that in 1944 he had been introduced for the first time to Heinrich Scholz, a mathematical logician, and only then did he get some notion on mathematical logic.

Immediately after the 1936 publication of Turing's paper, Heinrich Scholz was one of the first to write to Turing's mother Sara to ask her to send him a copy of his paper, which she did. Scholz wanted to incorporate it as an item entry in the *German Encyclopedia of Mathematics*. Hodges (1983), p. 124, refers to two postcards that Turing's mother received from Scholz—dated March 11 and 15, 1937.

Zuse developed independently ideas like those in C. E. Shannon, 'A Symbolic Analysis of Relay and Switching Circuits', *Transactions of the Institute of Electrical Engineering*, vol. 57 (1938), pp. 713-723. Compare this publication with '*Ansätze einer Theorie des allgemeinen Rechnens unter besonderer Berücksichtigung des Aussagenkalküls und dessen Anwendung auf Relaisschaltungen.' Nepublikovaný rukopis, Zuse Papers 45 (1943): 018* of Zuse. It is an account of the general theory of calculation, in particular of the application of the calculus of statement composition to problems of calculation, with special reference to switching theory. Zuse (1976), in Metropolis (1980), pp. 615-619, provides an additional detailed account of the translation of logic and of algebra to the switching of circuits.

20] References to cryptography, and in particular the decoding of the Enigma during World War II, are many and diverse. On the cracking of the Enigma key code, see Hodges (1983), pp. 157, 170-176, 179, and particularly 374. According to Hodges, a meeting-conference was held in Warsaw on 24th July 1938 of representatives of the secret services of France, the UK and Poland, in which the Poles disclosed information concerning the Enigma. According to C. Brown (1975), Turing and Alfred Knox (then Turing's boss at Bletchley Park), were sent after June 1938 to verify certain information about the Enigma that the Poles had reconstructed. Hodges (1983) p. 157 claims that Turing reported to Bletchley Park only on 4th September 1938 after his return from the USA, so that it was only Knox who participated in the discussions held with the Poles. Anyway, these had no success.

Randell (1976) in Metropolis (1980), p. 54, in his account on the Colossus, observes that 'Bombas' (which should be spelled according the Polish language) operated on the sieve principle with photo-electric cells, like the sieve in Lehmer's listing of primary numbers. (The method is of Eratosthenes, who introduced it over two thousand years earlier; Lehmer invented an automatic tool to reproduce it.) See also references to the sieve process in Part I.

The best account as to the cracking of the Enigma key code is that of M. Rejewski, 'How the Mathematicians Deciphered the Enigma', *Annals of the History of Computing*, vol. 3 (1981).

21] Hodges (1983), pp. 177-178; R. V. Jones, *Most Secret War*, Hebrew edition (1984), p. 61.

22] Morse devised his code notation to fit the frequency of letters of the English alphabet: he allotted the more frequent letters the fewest number of dots and dashes.

23] Hodges (1983), pp. 166-288; R. V. Jones, *Most Secret War* (1979), pp. 200-208, 267, 327, 413, and 663.

David Kahn, *The Code Breakers* (1973), p. 23; this is an abbreviated version of his 1967 edition. Anthony Cave Brown, *Bodyguard of Lies* (1975), pp. 15 and 22-34.

24] I learned about this method from discussions with Professor J. Gillis at the Weizmann Institute, Rechovot, Israel, in 1985.

25] According to Brown (1975), a device was constructed according to the specifications of the British Foreign Office made in a contract signed in 1938 with the British Tabulating Machine Company at Letchworth, not far from where the Bletchley Park team lived and worked. The chief manager of the project was Harold Keen, who led a team of twelve. Keen claims that it was not a computer nor anything similar, but a machine built for this sole purpose. Yet it was not a tabulating machine, as at times it was used to decipher: 'What it did was to match the electrical circuiting of the enigma. Its secret was in the internal wiring of (enigma) rotors, which "the bomb" sought to imitate' (Brown 1975, p. 22). And here is an unequivocal description of a simulator. Brown (1975), p. 23, also reports that on September 3, 1939, the expiration date of the French-British ultimatum, the bomb was already in action and the material obtained from it was codenamed 'Ultra'. According to Hodges (1983), p. 191, however, the bomb was operational only by May 1940. Possibly this is a confusion between the Polish and the British tools. It is possible that Brown refers to the Polish 'bombas' that were already operational by September 1939, earlier than the British 'bombs'. It is also historically, chronologically and geographically feasible that the British, who were well aware of the existence of the Polish 'bomba', were in a position to develop their own bomb, Turing being present at Bletchley Park since September 1938.

26] See note 23 above, in particular Hodges (1983) and Randell (1976) in Metropolis (1980), pp. 53-61. Randell bases his own surmise on Kahn (1967) and Brown (1975). Brown's version is possibly incorrect; Hodges' version (1983), p. 191, is different. According to Hodges, Turing's prototype of the bomb was completed by May 1940 and a more advanced model went into action by August that year. Hodges' version draws on more sources. F. W. Winterbotham, *The Ultra Secret* (1974), one of the first publications on this issue whose author was then in charge of security for Bletchley, who also mentioned a device that was first called the Eastern Goodness, and then, in the 1940s, the Oracle (p. 15).

Professor Peter Calvocoressi (1974) claims that Bletchley used 'machines called bombs which were prototype computers'. Gordon Welchman, in *The Hut Six Story* (1982), says: 'We thought very little, in those days, of who should take credit for what.' I. J. Good (1976) in Metropolis (1980), pp. 31-45, writes that when he arrived at Bletchley Park by May 1941 the bomb was already in operation (pp. 33-37).

27] On the dispute between the Americans and the Britons on the acquisition and production of bombs, see Hodges (1983), pp. 235-6 and 262-3. He refers to a debate about whether to produce three hundred and sixty units in the UK or alternatively to produce one hundred such units in the USA. The evidence of the existence of

American bombs (or their equivalent) before September 1943 appears in Robert A. Atha, 'Bombe! I could hardly believe it!', *Cryptologia* (Oct. 1985), pp. 332-336.

28] Hodges (1983); also note 25 above.

29] Good (1976) and Randell (1976), both in Metropolis (1980), as well as Hodges (1983), pp. 220-227.

30] Hodges (1983), pp. 269-270, 236-237, 245-248 and 284-285. See also Brown (1976), pp. 64-100. Also a discussion held between Stibitz and the author on 17th October 1986 at Darmstadt College.

31] Hodges (1983) p. 299; discussion with Stibitz, see note 28 above.

32] Good (1976) in Metropolis (1980), p. 40; Randell (1976) in Metropolis (1980), pp. 56-65); and Hodges (1983), pp. 267-268 and in particular pp. 225-226.

33] Randell (1976) in Metropolis (1980), pp. 64-89, provides a detailed and updated account on it. So does Hodges (1983), pp. 267-268, 277-278, 299-302 and 320 (relying on Randell, 1976).

34] In Hodges (1983), p. 268 and p. 554 footnote 7: 'The essential part AMT [Turing] played in this development was in providing a statistical theory: not the machine but the purpose for which it would be used.' See also I. J. Good, 'Studies in the History of Probability and statistics 27. A. M. Turing's Statistical Work in World War Two', *Biometrica* 66 (1979).

35] On Turing's construction of the binary multiplier at the physics laboratory, Princeton, see Hodges (1983), p. 138.

36] The manual decoding process was performed in a similar manner to Zuse, as applied in his calculating forms.

37] See the joint letter to Churchill dated 21st October 1941 that Turing participated in. See Hodges (1983), pp. 219-221.

38] See note 25 above.

39] According to Brown (1976), a division of the responsibilities for deciphering appeared in February 1942. The USA was in charge of obtaining the intelligence on the Japanese Sector and the deduced deciphered material there was called 'Magic'; the UK was in charge of obtaining the intelligence on the German Sector and the deduced deciphered material there was called 'Ultra'. This division was deceptively meant to conceal the existence of material obtained from breaking the key codes (based on Brown, p. 64). The signing of this treaty of intelligence cooperation between the USA and the UK, made it possible ask Turing to go to the USA in November 1942 to test the reliability of the American voice-encoding systems (perhaps the X system built at the RCA Laboratories). It was meant to be applied for coordinating personal communications between Roosevelt and Churchill and a very limited number of top ranking officers in all some twenty persons, on international coordination of the war effort. Upon his return to the UK in March 1943, Turing began work on his own development of a small binary voice-encoding device called the 'Delilah' which was of the size of a TV set, much smaller than the RCA's X device that occupied a large room. See Hodges (1983), pp. 269-294.

40] Goldstine (1972), p. 218:

> 'The logical complexity of the ACE is not surprising since Turing had a preference for this type of activity to engineering. The type of complexity Turing proposed, while attractive in some respects, did not in the long run flourish and the selection weeded it out.'

Note the appeal to evolutionary epistemology.

41] J. V. Atanasoff, 'Computing Machine for the Solution of Large Systems of Linear Equations' (unpublished memo), Ames, Iowa: Iowa State College (Aug. 1940). Reprinted in full in Randell (1982), pp. 315-335.

42] for Wiener's claim see his book *Cybernetics* (1948), in the 1956 edition, pp. 3-4 and in the bibliography there, pp. 229-240. It is repeated in several letters and proposals from Wiener to Bush that I found in October 1986, in the MIT archive in Box 2, Folder 58. The first letters of interest are of September 20 and 21, 1940. They are identical in content and comprise four typed pages. Another letter, bearing the date of September 23, 1940, refers to that proposed machine. Bush's letters of replies to these, are dated September 23, 24 and 25, 1940. In a letter of October 19, 1940, Bush informs Wiener 'that it is debated in two places'. A comprehensive memorandum, 'Mechanical Solution of Partial Equations', in which Wiener discusses the machine, is in Box 11, Folder 557 that contains eleven pages in all. In the same Box, Folder 558, has an additional memorandum bearing the heading 'Scope etc. of a Suggested Computing Machine'. It comprises twelve pages and describes the machine's components and its operational features. The main point of this memorandum is that in it Wiener speaks on the utilization of existing vacuum tubes, and he is aware the speed of fifty thousand operations per second that such an apparatus can reach. For the Wiener memorandum on this issue, see also 'Memorandum on the Scope etc. of a Suggested Computing Machine', in Randell (1980) 'Bibliography' in Metropolis (1980), p. 647; as well as Williams (1984), 'Memorandum on the Mechanical Solution of Partial Differential Equations', File 558 and draft 557 of the same file, Winner Papers, Box 11, MIT Archives. According to this report, which was never published, apparently, this memorandum is dated September 23 (according to Williams, 21), 1940. Perhaps this memorandum resulted from the Hanover meeting held in September 10-12, 1940, where Stibitz exhibited the functioning of the complex computer. This 12 pages long report concentrates mainly on the technique of definite differences to solve marginal values in the partial differential equations. In the memorandum is a proposal to construct an electronic calculating device that would mechanize the iterative process of four binary points that would represent any decimal digit, and all by means of a binary adder and a type of scanning apparatus that would have four reading heads and one writing head. It proposes several technologies that would suit these tasks, with a clear preference for adopting magnetic recording. On the last page (12) in the last paragraph that is very brief and vague, Wiener proposes an 'Electronic machine capable of performing a rapid sequence of operations such as addition and multiplication on the data read in, before printing the result in binary.' Mauchly's second wife Kathleen claims in *Annals of the History of Computing* (April 1984), p. 126, that at the Hanover Conference Wiener and Mauchly decided that 'electronic is the way to go’. Mauchly’s name does not appear on the list of the participants of that conference, as published by the *American Mathematical Society Bulletin* in November 1940. He was there and even received a teleprinter punched paper tape output that he later presented to his readers in the Ursinus College paper.

Williams (1984) examined another claim of Wiener (1948) that by September 1936 (when he was on a sabbatical in China) he sent Bush a drawing of an electric device to solve simultaneous sets of equations. Wiener sent this together with his remarks to Bush’s famous draft of a lecture that he later delivered—as a part of his Gibbs Lectures—on January 2, 1936. What Wiener proposes is an analog calculating device. Bush was then the dean of the school of engineering and vice president of MIT. Bush passed Wiener’s proposal to Harold Hazen, who was then the head of the department of electricity, who did nothing with it until April 1938 when he returned it back to Wiener with a note that he had found the drawings ‘in a pile of old papers’. Hazen apologized, explaining that they ‘were so long buried’ and re-contacted Wiener to raise the matter afresh. The idea was finally abandoned. Still, Wiener said in one of his letters that he had succeeded in constructing such a model in China. See Williams (1984), pp. 15-16 and 62-63. This information comes from the following sources and correspondence:

N. Wiener to V. Bush, September 22, 1935, MIT Archives, Faculty Academic Staff Records, N. Wiener’s File.

V. Bush to N. Wiener, three pages of schematics, ‘Sketch of Invention by N. Wiener’ at Tsiang University, Peking, China, September 22, 1935, in N. Wiener’s *Papers* with a note from Harold Hazen 11 April 1938.

After Wiener’s proposal was ‘stuck’ with Hazen for a long time, it was directed to Bush. And finally:

H. L. Hazen to N. Wiener, 11 April 1938, in N. Wiener’s *Papers*, MC-22, Box 1, File 49. ‘Correspondence January-September 1938’, MIT Archives.

In Williams (1984), pp. 240-253, there is also a comprehensive and deep treatment on this issue of Wiener’s proposal from 1940.

However, Wiener’s proposal was finally rejected by a pragmatic argument, which was that it was a long term projection, whereas at the time (1940) they were being prevailed upon to provide short range or immediate solutions which were practical for the impending war, a claim without any concrete foundations: ‘…I feel sure that the type of talent needed to perfect such a device in its mechanical aspects is bound to be heavily engaged at the present time on defense research matters of various sorts.. it appears essential that at the present time those individuals who are particularly qualified along these general lines be employed as far as possible on matters of more immediate promise,’ Bush to Wiener, 31st December 1940, Wiener’s *Papers*, Folder 58.

43] See Bush’s memorandum on the ‘Arithmetical Machine’ March 7, 1940, reprinted in full in Randell (1982), pp. 337-343, and on the Rapid Arithmetical Machine, *Ibid.*, p. 259. See also K. L. Wildes, *The Digital Computer-Whirlwind*, Cambridge MA, MIT Press, 1976, as well as K. L. Wildes and N. A. Lindgren, *A Century of Electrical Engineering and Computer Science at MIT, 1882-1982*, Cambridge, Mass.: MIT Press, 1985; an account on this project is given in Chapter 15 there.

44] See Atanasoff (August 1940) in Randell (1973), p. 307. Atanasoff coined the terms 'analog' and 'computer'.

See also Goldstine (1972), p. 123. Mauchly's diary entry for August 15, 1941, reports that Atanasoff coined the term 'analog' or 'impulse' for a calculating device. Reference to this also appears in Randell (1973), p. 289, and in Kathleen Mauchly (April 1984), p. 131; the term 'digital' Mauchly ascribes to Stibitz. According to Kathleen Mauchly (1984), p. 126, he did that in the Hanover meeting.

45] J. R. Berry, 'Clifford Edward Berry, 1918-1963: His Role in early Computers', *Annals of the History of Computers* (Oct. 1986), pp. 365-366.

46] According to Randell (1982), p. 434: Atanasoff and Brandt, 'Application of Punch Card Equipment to the Analysis of Complex Spectra', *Journal of the Optical Society of America*, vol. 26, no. 2 (Feb. 1936), pp. 83-88 has a detailed account of the application of a tabulator integrated with a homemade cross connecting board, that enables setting numerical values.

47] See Stibitz (1940) in Randell (1973) and other versions of Stibitz in G. R. Stibitz, 'Early Computers' in Metropolis (1980), pp. 479-483; and Evelyn Loveday, 'The Relay Computers at Bell Labs', *Datamation* (April-May 1976), pp. 35-49.

48] Stibitz (1967), pp. 39-41.

49] T. R. Hollycroft, 'The Summer Meeting in Hanover', *Bulletin, American Mathematical Society*, 46 (1940), pp. 859-861; also Stibitz (1976), p. 481 as well as Stibitz (1967), pp. 43-44.

50] O. Cesareo, 'The Relay Interpolator', *Bell Lab. Records*, vol. 23 (1946), pp. 457-460. Reprinted in full in Randell (1973), pp. 247-250.

F. L. Alt, 'A Bell Telephone Laboratory's Computing Machine', *MTAC*, vol. 3 (1948), pp. 1-13 and 69-84.

51] J. Juley, 'The Ballistic Computer', *Bell Lab. Records*, vol. 24 (1945), pp. 5-9. Reprinted in full in Randell (1973), pp. 251-255. S. B. Williams was the chief engineer who participated in the design of all other Bell models after Stibitz was lent to the NDRC. Williams' contribution is notable and significant. See also the opening written by Randell in the section on Bell Computers in Randell (1973), pp. 237-239.

52] There are many references to the creation of 'Fictions'—electro-magnets against electronics in the construction of large scale calculating machinery in the USA. Here are a few: Goldstine (1972), pp. 150-154 and 143-147; N. Stern, 'The Eckert Mauchly Computers Conceptual Triumphs Commercial Tribulations', *Technology and Culture*, vol. 23, no. 4 (Oct. 1982), pp. 569-582; and Williams (1984), pp. 374-399, in which the gist and an extract of this appear; see also T. P. Hughes, 'ENIAC: Invention of a Computer' (1975), p. 163.

53] See above, chapter 1, Section on 'Analog Calculating Devices'. E. C. Berkeley (1973), Randell (1973), and Randell (1982) have comprehensive bibliographies on analog calculating means.

54] Martin O. Holoien, *Computers and Their Social Impact*, London (1977), pp. 29-36; Jeremy Bernstein, 'The Analytical Engine', in J. Diebold, ed., *The World of the Computer*, NY: Random House (1973), pp. 35-43. The original source is a chapter in Jeremy Bernstein, *The Analytical Engine*, NY: Random House Inc. (1963). Page 51 there discuses Aiken's development of the two calculating machines for solving polynomials:

> 'The theoretical aspects of the thesis involved the solution of so called non-linear ordinary differential equations, which could be done only by means of numerical approximation... Aiken began considering possible methods of doing the long computations on machines, and soon invented a machine that could evaluate simple polynomials. After a year or two, during which he invented variations on this machine that could solve more complex kinds of problems, it occurred to him that all these machines were, in their logical organization, essentially identical, capable of dealing with any of those problems'.

I have found no other corroborating source to support this evidence of Bernstein. In a discussion on this point with Professor I. B. Cohen at Harvard on October 16, 1986, I learned from him that Bernstein had a series of interviews with Aiken, and the above account rests on these interviews. Bernstein graduated in physics, and was then employed as science correspondent for the *New Yorker*. Professor Cohen recalled that R. W. King had vaguely claimed that Aiken had constructed something. Richard J. Purcell, Aiken's classmate, remembers that Aiken had an analog hydraulic machine.

55] On the need for a suitable calculating machine for scientific calculations, see Aiken (1937), reprinted in full in Randell (1973), p. 192.

56] On the distinction between calculating devices required for commercial purposes and those required for scientific calculations, see Aiken (1937) in Randell (1973), pp. 192-193.

57] There are several versions of the story of the connection between IBM and Aiken. One is found in Randell (1973), p. 187. A different version is Goldstine (1972), p. 111. A third version is in I. B. Cohen's introduction to G. Chase (1952), *Annals of the History of Computing* (2:13, July 1980), pp. 198-200. Wallace Eckert extrapolated this relationship between Aiken and IBM, as described in the following: http://www.columbia.edu/cu/computinghistory/eckert.html.

58] H. H. Aiken and G. M. Hopper, 'The Automatic Sequence Controlled Calculator'. *Electrical Engineering*, vol. 65 (1946), pp. 384-391, 449-454 and 552-528. Reprinted in full in Randell (1973), pp. 199-218. I recommend a comparison between the brief historical introduction of Aiken (1937) with the account proffered by Aiken and Hopper (1946), in order to inform the historiography regarding the narratives adopted later on by other authors on the history of computing and computer science. See the opening chapters or introductions in these books. See also Chapter 1, note 16 above.

59] See note 48 above.

60] W. J. Eckert, 'The IBM Pluggable Sequence Relay Calculator', *MTAC*, vol. 3, no. 23 (July 1948), pp. 149-161.

61] Two large symposia were held at Harvard by Aiken to inaugurate Mark II (1947) and Mark III (1949): Symposium on Large Scale Digital Calculating Machinery, January 7-10, 1947 and Symposium on Large Scale Digital Calculating Machinery September 13-16, 1949. The most distinguished experts in digital automatic calculation participated. For a detailed report on the sessions and the participants of the first symposium, see *MTAC*, vol. 2, no. 18 (April 1947), pp. 229-238. 336 representatives from academia, industry and government participated. The opening address was 'The work of Charles Babbage', by Richard Babbage, great-grandson of Charles Babbage and a correspondent for a Canadian agriculture magazine. The earliest correspondence between Aiken and the Babbage family dates from 17th April 1946, which is perhaps indicative as to time that Aiken adopted Babbage as his spiritual mentor.

62] W. J. Eckert, 'Electrons and Computation', *The Scientific Monthly*, vol. 67, no. 5 (Nov. 1948), pp. 315-323. Reprinted in full in Randell (1973), pp. 219-228.

63] For example, in 1895 Otto Schaeffler (1838-1928) developed a tabulator with a control apparatus based on the connecting board of a manual telephone exchange. In the same year Hollerith tried the same thing for accounting purposes at the New York Central Railway Station offices.

Already in the 1930s, the Austrian engineer Gustav Tauschek (1899-1945) incorporated a photo-electric read-write input-output for a calculating device to compare data using IBM equipment. For an account of Tauschek's and Schaeffler's works see Zemanek (1976) in Metropolis (1980), pp. 595-601.

Regarding the IPM device constructed during World War II by integrating IBM equipment in Germany with a connecting board of the manual telephone type, see H.-J. Dreyer and A. Walther, *'Der Rechenautomat IPM Entwicklung Mathematischer Instrumente in Deutschland, 1939 bis 1945'* (19 August 1946), reprinted in full in English translation in Randell (1973), pp. 151-153 and in H. Zemanek, 'Central European Prehistory of Computing', in Metropolis (1980), pp. 595-601.

Even in Japan some development of punch equipment took place, as reported in Ryota Suekane, 'Early History of Computing in Japan', in Metropolis (1980), pp. 575-578. The first known example of this was a manual punch developed in 1905; it had no follow-up. Dr. Nakajima of the Nippon Electric Company developed a punch machine. More or less at the same time (1920s), Hollerith's punch machines were exported to Japan until the war (1941): some thousands of them arrived there before the war broke out. In 1938, Shikawa of Fuji Electric developed a binary relay circuit. In 1939 Dr. Ono, a professor of mathematics at the University of Tokyo, intended to use binary notation for a statistical calculating device; he completed constructing it only in 1951. In 1936, Dr. Nakajima of the Nippon Electric Company published a paper on switching circuits, accrediting the influence of G. Birkhoff's famous 1935 development of lattice theory. This led to the formation of a group of electrical engineers interested in mathematical logic and switching circuits.

64] See Kathleen R. Mauchly (April 1984), p. 137 and Randell (1973), p. 290. Compare these with the version provided in Goldstine (1972), p. 149, in particular footnote 1: 'The dating of August 1942 is somewhat peculiar since Brainerd's acknowledgment of the document bears the date of 12 January 1943'.

65] The document that Brainerd (Moore School) sent comprises thirty-two pages. There are two versions of the heading of the document's title. The first is: 'Report on an Electronic Diff. * Analyzer', Moore School of Electrical Engineering, University of Pennsylvania, Philadelphia, April 2, 1943. The asterisk indicates a footnote located on page four of the document:

> 'The word Diff. * is deliberately abbreviated. Present differential analyzers operate on the basis of integrating continuously, i.e., by differential increments; the electronic analyzer, although it is believed that it would be both speedier and more accurate, would operate using extremely small but finite differences. The abbreviation 'Diff. *' may thus be considered to represent 'difference' rather than 'differential' in the case of the electronic device.'

Goldstine (1972), says in a footnote on p. 149 that the author of the report of April 2, 1943, is Brainerd. Goldstine says that this is the first draft. Randell (1973) bibliography says on page 442, the author of this document is anonymous and it bears the date April 8, 1943. I attempted to explain the date discrepancy by suggesting that although the report was completed on April 2, since it was submitted to the military authorities for a meeting which was due to be held on April 9, and since photocopying was still extremely rare at that time, it was re-typed in several copies in an Army office where it was given the date April 8, 1943. Luckily, there is a great mass of primary source material regarding the start of ENIAC project among the records of the trial 'Validity of ENIAC Patent and of Possible Infringements of this Patent. Honeywell Inc. Vs Sperry Rand Corp. Illinois Scientific Developments Inc., US District Court, District of Minnesota, Fourth Division' (1967-1974). This raw material incudes tens of thousands of pages of valuable original documents and sworn testimonies of many of the people involved. It is yet to be examined with the thoroughness that it deserves. Randell (1979), Appendix 2, has a description of these records, and of the indices which exist to them.

It may come as little surprise that this wild surmise of mine turns out to be false. I have decided to leave it here because it has led me to find the desired documents. For, studying the secondary literature, I came across a number of references to the 1943 'Report on an Electric Diff. * (or Difference) Analyzer'. What intrigued me, and drew my attention to the problem, was the two different references to the same report. Some gave the date of 2nd April 1943 and the title 'Report on an Electronic Diff. * Analyzer'; others moved the date to 8th April 1943 and gave it a slightly different title: 'Report on an Electronic Difference Analyzer'. At first I paid no attention to the minor discrepancy between 'Diff. *' and 'Difference', assuming that the references related to two otherwise identical versions of the same report. My curiosity was piqued by the different dates (April 2 and April 8, 1943), and also by the assertion in Randell's bibliography (Randell 1973, p. 442) that the report was anonymous.

Many scholars who write after the event of the ENIAC Patent Suit, and who have studied the mass of carefully catalogued primary source material that is readily available, have nevertheless overlooked the inaccuracy of the data.

The problematic authorship of the report was first raised in part in the debate between Burks and Brainerd in 1981. Unfortunately, the primary sources provide little or no evidence as to this authorship. The report is described in its title as having been 'submitted to the Ballistic Research Laboratory, Aberdeen Proving Ground by the Moore School of Electrical Engineering, University of Pennsylvania'. To make things worse, even the well-known 1942 memorandum by John Mauchly that appears in the report as Appendix A does not bear his name. Goldstine (1972) referred to the April 2 Report as a first draft and claimed that the author was Brainerd. Goldstine states there, on page 149, footnote 2, 'On April 2 1943 at my request Brainerd prepared a report for submission to Gillon'.

Another important secondary source is T. P. Hughes (1975) of the University of Pennsylvania, who made a thorough study of the development of ENIAC, based on personal interviews, on the Moore School archives (which include transcripts of the ENIAC Trial), as well as on Goldstine (1972). Hughes (1975, p. 156) states, 'Brainerd was asked to write a proposal for the machine, which was submitted to the Laboratory [BRL at Aberdeen; A. A.] on April 2, 1943, followed by a more complete report on April 9'. This is inaccurate. The 'more complete report' is from 8th April 1943, while the meeting itself was held on 9th April 1943! This renders the minutes both prophetic and in retrospect!

66] For a detailed account on the BRL—Ballistic Research Laboratory—see Goldstine (1970), in Fernbach and Taub, eds. (1970), pp. 51-102, as well as Goldstine (1972), pp. 127-139. On the situation there since Goldstine's appointment, see Goldstine (1972), pp. 165-166.

67] one may glean this impression from Goldstine's book (1973), thought I have doubt on how crucial was his influence on the initiation of the project.

68] See Goldstine (1972), pp. 154-155; Mauchly (1976) in Metropolis (1980), p. 545.

69] P. Eckert (1976) in Metropolis (1980), p. 526, states that the 'I' in 'ENIAC' stands for integrator, as the machine was devised to help sell the Pentagon what the BRL was getting would compute firing tables, which were, in 1943, the greatest need of ordnance'. For the acronym ENIAC, see Goldstine (1972), p. 150. The US Army, like other armies, has a long tradition of using acronyms.

70] Mauchly's papers are in the Van Pelt Library Special Collection at the University of Pennsylvania. As to Mauchly's awareness to George Boole, in Box 5, Folder I.55, there is a nine-page document in the handwriting of Mauchly, seemingly of 1935-1936. Mauchly's interest in mathematical logic and the formalization of reckoning and calculating seems to me probably unconscious. In a letter to his sister Martha of March 21, 1925, he wrote, 'It is my folly which prompted me, more than once, to formulate one rule for every situation and to attempt to solve every problem by the same rule'.

Part 2 Summary

1] Mauchly's papers, Van Pelt Box 1, Folder 2.

Chapter Five

1] In Randell (1982), pp. 195-196.

2] *Ibid.*

3] Aiken-Hopper (1946) in Randell (1982) pp. 199-218.

4] For example, John Mills, 'Communication with Electrical Brains', *Bell Tel. Quarterly*, vol. 13 (1934), pp. 47-57.

5] Randell (1982), p. 196-7.

6] *J. von Kluge, 'Frequenz Untersetzung durch Stromrichter bei kapazitiver Last', Physikalische Zeitschrift, vol. 35* (1934), pp. 275-279. This specific article concerns the application of electrical capacitors. Other articles in the same issue concern the use of various vacuum tubes, referred to as Wynn-Williams counters of 1932.

7] Eckert, 'Thoughts on the History of Computing', *Computer* (Dec. 1978), p. 58.

8] Edmund Callis Berkeley, Thomas Nall Eden Greville, and Henry M. Sarason. *Boolean Algebra (the technique for manipulating 'and', 'or', 'not', and conditions) and Applications to Insurance*. E. C. Berkeley and Associates, 1952.

9] In Randell (1982), pp. 171-173.

Chapter Six

1] 'First Draft': John von Neumann, 'First Draft of a Report on the EDVAC', Contract no. W-670-ORD-4926, Moore School of Electrical Engineering, University of Pennsylvania (30 June 1945). Reprinted in full in Randell (1973), pp. 383-392.

As seen in discussions above, this Report is part-and-parcel of the contract between the US Army Ordnance Department and the University of Pennsylvania. This document is ascribed to von Neumann, whose name appears in the heading of opening page in the original Report. The initial publication run was 70 copies; the second edition had more. It is known, for example, that even visitors who came from the UK received copies of it. From a discussion held on October 23, 1986, at Goldstine's office at the American Philosophical Society, Philadelphia, concerning this report, I may conclude the following. a) When the document was published, von Neumann was at Los Alamos. b) It was Goldstine who had edited the report, according to written material that von Neumann sent then from Los Alamos. This I conclude also from a letter (von Neumann to N. Wiener, MIT Archive MC22, Box

2, Folder 68) of April 21, 1945. c) Goldstine told me that it was he who decided to circulate more copies of this document, as permitted by the security authorities, and that it was well within the scope of his power. And yet, the original documents of ENIAC, referring to the security and classification of ENIAC and EDVAC, specified that only five copies of any document related to these projects may be published. Of these, two were designated for military history archive storage, so that only three were for the use for which they were made. In our discussion I argued that it was he, Goldstine, who wrote the report, much as he tried to deny it; and this I can tell from the style of writing that is more Goldstine's then von Neumann's. We parted in disagreement.

The 'First Draft' has explicit definitions for this sort of device; these are then further discussed in a detailed account on the parts and the components to include in such a calculating device, and in particular the unequivocal preference for binary notation. The opening places emphasis on the importance of the logical controls.

In the nickname 'Trinity Paper', attention focuses upon the report: Burks, Goldstine, von Neumann, 'Preliminary Discussion of the Logical Design of an Electronic Computing Instrument', part 1, vol. 1, Princeton: Institute for Advanced Studies (June 28, 1946). This document, first published in von Neumann's *Papers* (1963) and in other places (see the bibliography by Randell and elsewhere), belongs to another contract, W-36-034-ORD-7481, which this time was signed between the Institute for Advanced Studies and the US Army Ordnance Department. From the outset this report was meant to contain four parts. The title 'Trinity' has a dual meaning; first, it indicates that it was authored by the three persons who had decided to build their own computer at Princeton; second, like Holy Writ, the paper required blind assent by all further development of the computer.

The first part of the report was intended to include a general description of the device and its logical technical aspects. In the preface the authors expressed their gratitude to Dr. John Tukey for his discussion with them and for his proposals to them. Later on, Tukey personally contributed a great deal to the development of the computer. The fourth part was never written. The report has an extensive elaboration on what was already written in the 'First Draft', but with its focus on further technical details such as the structure and properties of the memory of the device. Already the 'Trinity Paper', displays an extensive use of terminology borrowed from physiology, such as organs, neurons, etc. A considerable number of copies of the report were published. The first edition had 175 copies, published in the USA and abroad. The second edition had 200 copies. On this see also Goldstine (1972), pp. 255-256.

2] J. P. Eckert, 'Thoughts on the History of Computing', *Computer* (Dec. 1976), pp. 59-60.

3] The author of this is Dr. Luis Austin, 'The Computer and Mankind', in *Introduction to Programming and Knowing the Computer, Unit 12*, Everyman's University, Tel-Aviv (1979) pp. 16-29.

4] 'Theory and Techniques for the Design of Electronic Digital Computers', Lectures delivered on July 28 to August 31, 1946, at the Moore School of Electrical Engineering, the University of Pennsylvania.

5] The term 'Large Scale Digital Computing Machine', introduced for the automatic program-controlled digital calculating machines, survived till the end of the 1950s. See, for instance, Frantz L. Alt, *Electronic Digital Computers: Their Use in Science and Engineering*, NY: Academic Press Inc. (1958) that is a historical survey. See the reference to the sheer mass and volume of the machine pages 17 and 18:

> 'The large-scale digital computing machine to which this section is devoted made its appearance in the 1940s. Earlier pioneering efforts seem to have had no lasting influence. The development, after 1930, of a large differential analyzer due to V. Bush and his collaborators and successors had shown that, in the analog field, computing machinery of such size could be built... The first of the large automatic machines was based on punched card techniques ... known as ... the Mark I ... The next two large machines were started under the influence of computing requirements resulting from the second world war ... One of these developments was undertaken by Bell telephone laboratories ... The other development project was undertaken for the US Army ... which resulted in the ENIAC, the first electronic computer.'

Alt was one of the mathematicians who worked at the Ballistic Research Laboratories at the Aberdeen Proving Ground. He was also in charge of the development of Bell's Mark IV (1944), a multi-purpose electro-magnetic device with some nine thousand relays and fifty terminals for teleprinting-teletyping. He later joined the US National Bureau of Standards and participated in their development of the Bureau's Standards Electronic Automatic Computer (SEAC) placed in May 1950 at the East Coast branch of the Bureau of Standards in Washington DC. Some claim that the 'E' in SEAC stands for 'East' and not for 'Electronic'. The second computer of the Bureau, the SWAC (1950), was constructed for the Western branch of the Bureau, as the letter 'W' indicates in the initials. It was placed on the campus of UCLA at the Institute for Numerical Analysis, established there in 1947.

See also Goldstine and von Neumann, 'On the Large Scale Computing Machines' (Nov. 1946). This report was published only in 1963 in von Neumann's *Papers*. It was prepared at the request of L. R. Ford, who was then the editor of the *American Mathematical Monthly*. For four or five years, Goldstine wrote, he had tried to obtain von Neumann's approval of a corrected version of their combined paper. The burden of work prevented its publication in any form. See Goldstine (1972), p. 216, note 10.

6] On the list of participants at the Conference on Advanced Computation Techniques, see *MTAC* vol. II, no. 14 (April 1946), pp. 65-68.

7] Turing participated in such missions that went to Germany immediately after the war's end (Hodges, 1983, pp. 311-312 and Wilkes, 1985). Reports of such missions appear in J. Todd, G. E. H. Reuter, F. G. Friedlander, D. H. Salder, A. Baxter, and F. Hoyle, *Applied Mathematical Research in Germany, with Particular Reference to Naval Applications*, Report no. 79, British Intelligence Objective Subcommittee, HMSO, London (1945). This is a report of an investigation held in Germany during June-July 1945; it includes a discussion of the visit to A. Walther at IPM Darmstadt and Göttingen. Page 63 there has a brief account of Zuse's calculating machines, written before direct contact with him was established.

8] On Zuse's 'invitation' or rather interrogation in London during 1946, see R. C. Lyndon (1947), pp. 355-359 and Zuse (1984). In our discussion on September 18, 1986, Zuse told me that they 'invited me to London in 1946' and that the invitation was, well, *an offer you cannot refuse*. He was diplomatically too reticent to describe it as an investigation proper.

On Alwin Walther's return from investigation in England (December 21, 1945), see De Beauclair (1986), p. 349 and R. E. Work, 'Automatic Calculating Machines', Interrogation Summary, Air Interrogation Unit, Air Division HQ, US Forces in Austria, APO 777, US Army (November 8, 1946). This report is four pages long, focusing on automatic calculating machines utilized in Germany for high speed aircraft and rockets. It concerns the interrogation of Zuse's partner Gerhard Overhoff. It includes an account of the S1 and S2, Zuse's special objective models (aerodynamics calculating machines). It also includes some detailed description, probably of the Z4. A brief account is also given of Zuse's firm, *Zuse Apparatebau*, established in 1943, with fifteen employees.

9] See Zuse (1984), pp. 67-69; De Beauclair (1986), pp. 347-348.

10] On the First Harvard Symposium see *MTAC*, vol. 2, no. 18 (April 1947). For the lectures there and their content see 'Proceedings of a Symposium on Large Scale Digital Calculating Machinery, 7-10 January 1947', *Annals of the Computation Laboratory of Harvard University*, vol. 16 (1948).

11] See *MTAC*, vol. 3 (1948-1949), pp. 57 and 133.

12] See *MTAC*, vol. 3 (1948-1949), p. 381. The Institute for Numerical Analysis was part of the National Bureau of Standards in the framework of the National Applied Mathematical Laboratory of the National Bureau of Standards.

13] See G. G Hoberg and J. N, Ulman Jr., *Glossary of Computer Terms*, Special Device Center, Office of Naval Research, Port Washington, NY: Long Island (1948); and *MTAC*, vol. 3 (1948-1949), p. 489.

14] For details see 'A Discussion on Computing Machines', held on 4th March 1948 and published in the *Proceedings of Royal Society of London*, vol. 195/A (December 22, 1948), pp. 265-287. The discussion included five speakers, who were, in their own right, important developers of such devices in the UK, before, during and after World War II. D. R. Hartree gave a historical survey on the development of digital computing machines. His survey starts with Babbage, the operating principles of the digital machines and an account of the developments in the USA, particularly Mark I and ENIAC. M. H. A. Newman spoke on the general principles of the design of all-purpose computing machines. He claims that at that point in time, all the essential behind general-purpose calculating machines were already in Babbage's plans for his analytical engine. Thus, Newman forms a direct link between Babbage and Turing:

> 'In modern times the idea of a universal calculating machine was independently introduced by Turing (1938) in connection with a logical problem ... and the construction of actual machines was begun independently in America, towards the end of the late war' (p. 271).

M. V. Wilkes spoke of 'The Design of a Practical High-Speed Computing Machine. The EDSAC'; J. H. Wilkinson discussed the development of 'The Automatic Computing Engine [ACE; A. A.] at the National Physical Laboratory', while A. D. Booth gave an account on what were then 'Recent Computing Projects' such as the Automatic Relay Computer that was part relay part electronic calculating machine, and was then nearing completion at the laboratories of the British Rubber Producers' Research Association in Welwyn Garden City, England (p. 284).

15] Conference on High-Speed Automatic Calculating Machines, 22-25 June 1949, University Mathematical Laboratory, Cambridge, UK.

16] Aiken's letter to Atanasoff of November 1946, Aiken's Paper Collection in Pusey Library, Harvard University, File UAV. 298. 2006.

17] For instance, H. M. Davis, 'Mathematical Machines', *Scientific American* (April 1949), p. 29.

18] ERA (Engineering Research Associates Inc.) of St. Paul MN. This team specialized in the development of calculating devices in general and those with magnetic drum storage in particular. In 1950 ERA published *High Speed Computing Devices*, later nicknamed the 'Yellow Book' because of the color of the paper that influenced the designers of electronic calculating devices even as far away as the Soviet Union. The Yellow Book served as a textbook for many years for people in this professional *milieu*. Impressively, the book, much like the 'First Draft' and the 'Trinity Paper', was part-and-parcel of a report prepared for the military authorities at the request of the Office of Naval Research. The book focuses, up to the smallest detail, on the design of computers' electro-magnetic and electronic components. The devices developed by the ERA team were, at the outset, for the National Security Agency (NCA). ATLAS I was termed as 'ERA 1101' and was delivered to the Georgia Institute of Technology in December 1950. ERA turned later into a very prosperous and successful manufacturer of scientific computers until it was taken overby Sperry Rand in 1952, enduring a fate similar to that of Eckert and Mauchly's company.

19] P. J. Denning, 'The Science of Computing: What is Computer Science?', *Scientific American*, vol. 73 (Jan.-Feb. 1985), pp. 16-19.

General Summary

1] J. P. Eckert (Dec. 1976), page 65.

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APPENDIX A

THE EVOLUTION OF THE TERM AND NOTION/CONCEPT OF 'COMPUTER'

Introduction

I have intentionally refrained from using here the term 'computer' for the class of automatic program-controlled calculating machines, since that term only became commonly accepted in the 1960s. Moreover, until then, various terms were used to designate the special characteristics of each of the automatic program-controlled calculating machines. In particular, let us not be confuse it with the term and notion (concept) of 'computer' that is so common today, the one that expresses and projects the property of information processing-manipulating of a very specific type of a device, one that may be classified under the definition of Turing's Universal Machine.

In order to conduct a deliberate and explicit distinction in this study of the issue of the evolution of the term and notion of computer, I refer here to a digital object capable of carrying out a series of operations in a well-defined and clear manner. This series of operations will be termed 'program'. What makes the computer unique is the ability and general-purpose property to change its program—its configuration, to use Turing's parlance—at will, without a reconfiguration of its physical structure or its 'hardware', in the sense of the various integrations of the components making up the device. Or, to employ Turing's Universal Machine definition, a machine capable of imitating any other known machine if we know its algorithm (pattern of functioning) or capable of imitating-simulating its configuration.

The term 'calculator' here denotes any digital calculating device that is a limited system capable of performing a single determined assignment, according to a fixed pattern of programs imprinted into its hardware. The physical structure, the hardware, of any device synthesizes specific properties of its operating plan. But it is of a fixed, predetermined design, such that any alteration or modification of its design imposes some physical modifications to the hardware itself as well.

The distinction between programming software and the hardware on the programming that is hardwired into its physical structure is of great importance. Many writers are confused about this; they thus confuse others. Such confusion concerns the medium in which the program is stored, particularly in consideration of how today many programs are imprinted on electronic chips. Software can be stored in or imprinted on a variety of storage means, which serve merely as storage mediums and no more. A storage medium may produce magnetized particles, electrical charges, optically in reflective di-bits, holographically, printed in bar codes and more. The difference between the various storage means can be exhibited in numerous properties, such as speed, cost, size, storage capacity, duration of storage, volatility, permanent or temporary storage, permanent or changeable storage, writing or reading only or writing and reading, etc. Hence, all permanently-fixed programs imprinted in the hardware of the device that cannot be altered by means of the components and that are parts of the original device, all according to the aims of end users, are defined and formed as integral parts of the hardware of the device in question.

The Evolution of the Terms 'Computer' and 'Calculator' until 1930

Webster's Dictionary says, the English terms 'computer' and 'calculator' were interchangeable and used synonymously to denote a mathematician carrying out calculations or employed in a specific type of calculation in an observatory or for a survey [1]. Only later, at the end of 19th century, were these two terms adopted to describe various types of calculating devices. The most common name for the office calculating machine was the desk calculator. To devices intended for scientific calculations, such as Babbage's engines, a titular adverb or adjective was added in order to denote the particular property of the device, as, for example, Difference Engine or Analytical Engine. An analog device, meanwhile, was known as an 'analyzer', such as the Harmonic Analyzer (1876) of Kelvin or the Differential Analyzer (1921) and the Net Analyzer (1929) of Bush. A clear cut distinction as to the character of the calculations separated simple arithmetic calculations from the analysis of general problems or more complex calculations [2].

The terms 'calculator' and 'computer' derive from the words 'calculate' and 'compute' that are of far older origin. In ancient Latin the terms *'abaculi'* or *'calculi'* denoted calculating pebbles on the abacus. The origin of the word *'calculi'* is derived from *'calx'* that denotes smooth limestones or pebbles, the source of the term for the element Calcium (lime). In 13th century France, these calculating stones were replaced by the term *'jetons calculi'*: marked coin-tokens replaced pebbles. These were usually imprinted with the likeness of the sovereign. In English these coin-tokens were termed 'counters' and in German *'Rechenphenningen'* ('counting pfennigs'). They were placed on a special piece of cloth or a board with location lines on a 'bureau' (in English, 'calculating board' and in German *'Rechenbrett'*), resembling the wires of the abacus. Moving the *jetons* on the calculating board according to a certain procedure resulted with the desired results. The English word 'reckon' and the German word *'rechnen'* meant, then, the arrangement of pebbles in a straight line. The French Revolution put an end to the use of *jetons calculi* in Europe.

The Latin term *'calculare'* derived in the Middle Ages from the Roman word *'calculi'*, and entered many languages. Ancient Romans made a clear status distinction between the *'calculones'*, and the *'numeraii'* or *'calculatores'*: only the former were of slave family origins. There were also *'granariis'*, highly respected geometricians who drew on sand (like Archimedes who met his death while drawing on sand). They differed in pay scale: *calculatores* got only 75 denarii and the *granariis* were paid 200 denarii.

In the mediaeval Latin, the meaning of *'computes'* was calculating or cutting a year's day table: the Latin word *'putare'* means to cut. Thence the word *'computes'*. The Latin word *'imputer'* means to cut or to engrave a sign on a tally, on a wooden gage or ruler marked according to a certain scale to indicate financial debt according to the sizes of the coins marked on the tally. *'Depurate'*, meanwhile, means to cut off something from the tally, namely, to change the gage.

The English word 'compute' and the French *'computer'* derive from the same Latin source of engraving or cutting a mark on the tally. The tally was used as a gage and an official document given in a contract for borrowing money; it served as a promissory note, on which the amount of money of the loan was marked. The borrower and the lender each got half of the tally, signed by the representative of the sovereign and marked with the expiry date of the loan.

The known marking and writing of numbers originated from the cuts made on the tally. The terms 'calculate' and 'compute' reflect two separate traditions that frequently meet. The first is that of a tool for counting—compute—concerned mainly with the counting of events such as holidays, years, durations and quantities. The other is that of a means of carrying out calculations using symbols. These two traditions do not relate to the numerical representation of the symbols that are widely known today. Computing became enshrined, and numerals gained mythical significance. Counting, in most civilizations, became a dominant factor not only with ritual and ceremonial meaning, but practical utility and impact [3].

Meaning of the Terms 'Computer' and 'Calculate' from the 19th Century Onwards

From here onwards, my discussion will turn on the significance of the terms 'computer' and 'calculate' from Babbage's time onwards. In the period 1935-1946 did not have as yet a crystallized discipline of computer science. The work in this *milieu* was by individual members of very small isolated teams acting independently. I estimate that in 1945 in the whole world the total community of people involved in this type of activity, with automatic program-controlled digital calculating machines, numbered approximately fifty people. I refer to those people who designed and developed these devices, excluding those engaged in the labor of their physical construction. The terminology applied then derived from images and metaphors taken from the domain of tabulating equipment, the mechanical calculators and other domains, according to the personal background of the individuals involved. Babbage, for example, borrowed his terms from industry in general and the textile industry in particular. He termed the processor 'mill', the memory as the 'storehouse' and the device, the machine in its entirety, as an 'engine'. The terms 'engine' and 'machine' were used in English as synonyms. Though they are very close in meaning, there is a distinction between them: they are not identical. Using the term 'engine', Babbage intended to indicate the device's motive power, in homage to the steam engine: 'I wish to god these calculations had been accomplished by steam'. His use of the term 'machine' for the digital calculating devices on the market was intended to distinguish them from analog instruments with such appellations as 'slide-rule' and 'planimeter', etc. In principle, the British carried on with the terminology a tradition set by Babbage for the automatic program-controlled digital calculating machines.

The first analogy between these devices and the human brain arose in meetings sponsored by Norbert Wiener and von Neumann in December 1944 [4].

In the 1920s and the 1930s, digital calculating devices bore the additional epithet: 'automatic'. Devices developed at the end of the 19th century displayed almost automotive properties. An automatic device either permitted the multiplication or division calculation to be performed in a single operation by the human operator, or had a limited storage capacity to retrieve or store intermediate results, or was moved by an electrical motor rather than manually. P. E. Ludgate's *Automatic Calculating Machines* says, 'It must be admitted, however, that a true automatic calculating machine belongs to a possible rather than an actual class' [Horsburgh (1914), p. 124].

Mechanical devices in general, automata, have a longer tradition then the mechanical calculating devices. The application of electro-magnets and electronics for counting preceded their application for control. Offspring of the tabulating equipment or the telephone exchange, the electro-magnetic switching equipment served as a central component in the first automatic program-controlled digital calculating machines, those of Zuse, Aiken and Stibitz. The term 'automatic', within the scope of the new descriptions of calculating devices, takes on a new meaning and refers to the overall operation of all the components of the system, not just to indicate a discreet property, as it was in the mechanical calculating machines of the 1920s and 1930s. Hence, before 1945 the term 'computer' related to a person whose occupation was to perform mathematical calculations. After 1945, the term 'computer' referred to a particular type of device, capable of performing the four basic arithmetical operations of addition, subtraction, division and multiplication by storing and automatically extracting intermediate and final results, and all that under the command and control of an apparatus activated by a program. Karl Pearson's (1919) *Tracts for Computers* provides calculating techniques for human computers, for mathematicians, not for machines.

Before 1935, the term 'calculator' referred to a digital device, usually an office desk calculator, able in most cases to perform the four basic arithmetical operations. In the period 1935-1945, the term 'calculator' was used synonymously with the term 'computer'. Stibitz told me that during the 1930s, the expression 'calculator' was used for the calculating machine, while the expression 'computer' meant a person, usually a woman, who carried out mathematical calculations. At Bell Laboratories and elsewhere, women were employed as human computers, and in Germany they were called *'Rechenrinen'*, 'calculating women'. Stibitz's distinction is also exhibited in a letter dated June 27, 1938, sent from the Carnegie Institute (Washington DC) to J. Mauchly that contains the following: '...your employment for two months from 1 July 1938 as Temporary Assistant Physicist and Computer at $100 a month.' [Mauchly's Papers, Van Pelt Special Collections, University of Penn., Box 7, Folder 1-86].

The common and accepted terminology to name computers prior to the 1960s was derived from the words 'computer' and 'calculator'. An examination and analysis of the words to name these devices, in publications and conferences, may provide important evidence regarding the confusion, inconsistency and lack of uniformity of terminology in those days. The common terminology in the titles of written sources of prior to the mid-1930s may also provide some scope to evaluate the various devices developed and designed back then. Babbage (1837) holds forth 'On the Mathematical Powers of the Calculating Engine'. By contrast, Percy E. Ludgate (1909) writes 'On a Proposed Analytical Machine' with the object of 'designing machinery capable of calculations however intricate or laborious, without the immediate guidance of human intellect' [Randell (1971), Appendix, p. 320].

L. Torres (1920) writes about a working model of an 'Electromechanical Calculating Machine'. The patent application of Zuse (1936) describes a method for the automatic execution of calculations with the aid of calculating machines; *'Verfahren zur selbsttätigen Durchführung von Rechnungen mit Hilfe von Rechenmashinen.'* Even the translator of the English version of the document in Randell (1973) was misled by this anachronistic approach and context, translating the term *'Rechenmachine'*, 'calculating machine', into 'computer'. Helmut Schreyer, Zuse's friend and independent developer, wrote in 1939 about a *'Technishe Rechenmschine'* that, in this case, was translated correctly into 'Technical Computing Machines' [see Randell (1973), p. 168]. Schreyer declared: 'We have a universal computing machine'. As I do not have access to the original German text, I have some doubt as to this translation and its context. The Frenchmen R. Valtat (1936) and Couffignal (1933 and elsewhere), being two of the pioneers in introducing binary notation into the design of calculating machines, still use the French term for calculating machines (*'Les machines à calculer'*) [5].

In 'On Computable Numbers' (1936), Turing speaks of numbers that can be computed, while Aiken's memorandum (1937) concerns a 'Proposed Automatic Calculating Machine' [6]. Even the name Mark I, of the first model built by Aiken et al, is self-evident: 'Automatic Sequence-Controlled Calculator' is a description of the method of operation of this device. It is, indeed, automatic and sequence-controlled. At Bell Laboratories, Stibitz

(1940) used the term 'computer' to entitle the heading of his internal memorandum [7]. In another memo dated 19th August 1940 [Stibitz collection at Dartmouth College, Case 20678], he uses the term 'calculator'. The Model I, constructed at Bell Laboratories, was called 'Complex Number Computer' (23rd February 1940), while the Model II was named 'Relay Interpolator' and the Model III was 'Ballistic Computer'. In his memorandum (August 1940), Atanasoff uses the expression 'Computing Machine' [8]. It is of interest that even in the Moore School's Reports of April 1943, they use the title of 'Electronic Diff. [difference] Analyzer' [9]. Meanwhile, Mauchly's memorandum (August 1942) was entitled 'The Use of High Speed Vacuum Tubes for Calculating'. Yet, the name that was finally given to this device was ENIAC, meaning 'Electronic Numerical Integrator and Computer'. However, some documents relating to ENIAC employ the terms 'computer' and 'calculator' interchangeably.

At times, the anachronistic tendency to use the term 'computer' in the modem sense is due to the current usage of the term 'calculator' to denote a variety of (pocket or office) calculating devices. So, for example, the use of the expression 'computer' in the title of ENIAC is somewhat peculiar, as in both models that directly resulted from it, the EDVAC (1944) and the EDSAC (1946), the letter 'C' in their initials denotes 'Calculator'. Also as regards the ABC, the Atanasoff-Berry Computer, the name here is misleading, because Atanasoff did not use that term at the time (1940). Instead, he used the term 'computing machine'. So historians may want to remember that the name ABC was given only in 1963 (to commemorate Berry), not because Atanasoff had come up with the concept of the modem computer as he claims. The developers of the automatic program-controlled digital calculating machines were aware of the difficulty of the choice of the proper terminology and the double meaning of those terms, and they referred to this very issue. For example, Atanasoff writes in the *Annals of the History of Computing* (July 1984, p. 234): 'I did use the word "computer" in my manuscript to characterize machines as well as persons.' T. H. Flowers, one of the Colossus designers, writes also in the *Annals of the History of Computing* (July 1983, p. 240), 'At the time I had no thought or knowledge of computers in the modem sense and had never heard the term used except to describe somebody who did calculations on a desk calculator.' As previously mentioned, Karl Pearson, in his *Tracts for Computers* (1919), used 'computers' to mean people who perform computations, explaining that the computers on his staff had 'been struck by the absence of any simple textbook for the use of computers.'

In the symposia and conferences held to inaugurate the various new devices, we may see the exertions related to deciding and adopting the proper name for these devices. The first such known meeting on this type of device was held at MIT between 29 and 31 October 1945, the Conference on Advanced Computation Techniques. Evidently, the expression adopted there derived from the root verb, 'to compute'. The first Harvard symposium to inaugurate Mark II that took place during 7-10 January 1947, was entitled 'Symposium on Large Scale Digital Calculating Machinery', as was the second Harvard symposium that took place during 13-16 September 1949 to inaugurate Mark III. Here we witness the use of the term derived from the root verb, 'to Calculate' the name 'Large-Scale' refers here to the property of executing extensive amounts of calculations and not to the sheer bulk of the device, even though it was often no less impressive.

In the Moore Lectures delivered between July 8 and August 31, 1946, to a group of twenty-eight selected scholars by a 'team' of the best professionals in the domain, including Mauchly, von Neumann, Eckert and Goldstine, who were directly involved in the development of such devices, some terminological novelties appear in titles such as 'Theory and Techniques for the Design of Electronic Digital Computers'. This appears also in the famous report of Burks, Goldstine and von Neumann (28th June 1946), 'Preliminary Discussion of the Logical Design of an Electronic Computing Instrument'. Here the expression derived from the root verb, 'to compute' prevails, to mean the characterization of the device.

In the UK, the first conference of this kind took place in Cambridge on June 22 to 25, 1949, and was entitled 'Conference on High Speed Calculating Machines'. At the National Physical Laboratories (NPL), at the end of 1945, Turing had prepared a report on a proposal to develop an 'Electronic Calculator'; later on the title of the report was replaced by a new one, 'Automatic Computing Engine' (ACE), using terminology that was either borrowed from Babbage, or in search of an independent approach. Professor Yehoshafat Giveon says that the initials ACE came to indicate that it was an ace, a veritable champion among all other calculating devices, likened to those pilots, the Aerial Aces, the knights of the sky of World War I, renowned for scoring the highest number of enemy aircraft downed. For, the developers wanted to emphasize the uniqueness of their device.

The computer of Manchester University (1949), called the 'Manchester Automatic Digital Machine' but known by the initials MADM or sometimes even MADAM, was virtually the first electronic device that incorporated a fast memory and internal storage in accord with the 'Trinity Paper'. Those who gave it its name had no longer any need to indicate that it is an electronic device, as this has already become the default assumption. By contrast, F. C. Williams and Tom Kilburn, two of the designers and developers of a small experimental electronic computing machine for the Royal Society Computing Machine Laboratory, housed in the Electrical Engineering Department of the University of Manchester, wrote in *Nature* (September 1948) on 'Electronical Digital Computers'.

IBM, as well as other commercial firms, hesitated to enter into the production of such devices before their marketing feasibility was established. IBM named its first such device (December 1944) 'the Pluggable Sequence Relay Calculator'. Its first electronic device, whose construction had ended by 1949, was the Selective Sequence Electronic Calculator (SSEC). In both cases, IBM named its devices according to their primary technical features and technologies, the first using plugs and relays, the second using electronic technology. The sequential control of both devices were stressed in their name. The term 'calculator' in the names of these devices denoted their principal function.

In Eckert and Mauchly's firm, the first models marketed were named BINAC (1946), or Binary Automatic Computer, and UNIVAC (1947), or Universal Automatic Computer. In both the letter 'C' stands for 'Computer'. It is important to note here that for the first time the term and property of universality is emphasized in the names for such devices. Yet, there is no mention in their names of their electronic technology. However, in the naming of the first device, the BINAC, the need was felt to mention a specific property of the device, to wit, the application of binary notation. In the UNIVAC this binary property was already evident and the emphasis passed to the main property of the computer in the modern sense of a universal machine, probably following the trend of Turing's (1936) paper. (There is no evidence for this.) Nevertheless, the preferred term for this device is 'computer'.

The confusion that existed then, in the use of expressions, terminology, etc., is readily illustrated by D. R. Hartree, one of the prominent users and constructors of calculating devices in the UK. He was aware of developments in the USA since 1935. In six articles written in the period 1946-1950 on the development of such devices, Hartree uses different terminologies for the same devices:

> 'The ENIAC, an Electronic Computing Engine', *Nature* (20 April 1946).

> Another account on a survey of a visit to the USA, published in *Nature* (12 October 1946), is differently titled: 'The ENIAC, an Electronic Computing Machine'.
>
> In 1947, the title of his lecture for the inauguration of ENIAC was: 'Calculating Machines—Recent Prospective Developments'.
>
> In 1948, he delivered a lecture before the London Royal Society titled: 'A Historical Survey of Digital Computing Machines'. The lecture treated Babbage's Engines, Aiken's Mark I, and ENIAC. Each and all were treated as the same type of device.
>
> In *Calculating Instruments and Machines* (1949), Hartree makes a distinction between devices like those of Babbage and those of Aiken, ENIAC and the SSEC.
>
> In Hartree's paper 'Automatic Calculating Machines' in the *Mathematical Gazette* (1950), he conducts a comprehensive discourse upon the properties of the EDSAC. Incidentally, the title of this article is identical to Ludgate's 1914 paper (see above).

From the early 1950s, there was an increasing tendency to use the term 'computer' for this type of device, as it better expressed the properties of the computer, while the term 'calculator' took on the meaning of a simple or advanced mechanical, electro-magnetic or electronic calculating machine, or what became known as the pocket calculator. Thus, in 1953 Claude Shannon wrote on 'Computers and Automata'.

Furthermore, the series of von Neumann's IAS (Institute for Advanced Studies) computers [10] at Princeton, the computers of the University of Illinois, and the computers of the American National Bureau Standards all used the term 'computer' as the name of their devices [11].

The Evolution of the Notion/Concept of 'Computer'

In this section I will try, very briefly, to show how the concept of the computer evolved, on the basis of sources written by designers of the automatic program-controlled digital calculating machines, such as Babbage, Aiken, Atanasoff, Stibitz, Bush, Mauchly, Turing and von Neumann.

Most of these designers referred in their writings to two aspects of their devices: the structure of the vital components in such a device, and the properties of the device. In these writings, a great deal of information appears, providing evidence on the thoughts of those designers on their devices during their design. It was clear to all of them that they were dealing with a new type of device. Even though most of them were not aware of the writings of Leibniz, where he proposed the construction of an algorithmic machine to decide on logical problems, they carried on from his very starting point. There is no evidence to indicate any historical continuity or tradition. The developers of the automatic program-controlled digital calculating machines wanted to solve certain problems that troubled them, but discussing these exceeds the scope of the current study. The problems they wanted to solve, the notions and terms incorporated in their designs, are very well expressed in their written memoranda. Aiken (1937) in his proposal gives an account of his device's concept in the following manner: 'At present the automatic calculator is visualized as a switching on which are mounted various pieces of calculating machine apparatus.' Aiken also provides a detailed comparison between a calculating device for commercial use as against one required for scientific calculations, adding: 'It is believed that the apparatus just enumerated, controlled by automatic switching, should care for most of the problems encountered.'

It is difficult to determine from Babbage's writings what exactly he meant by his Analytical Engine. Therefore, Babbage's grasp of the concept of the computer as according to today's notion remains controversial. Only Ada Lovelace's explication and commentary on Babbage's Analytical Engine are unproblematic.

V. Bush, in his 'Instrumental Analysis' (1936), makes a distinction between analog and digital devices. Bush calls for the development of calculating devices that have central control apparatuses. He also noted the gap between the formal mathematicians and the constructors of calculating devices. He tried to bridge this gap between the methods of calculating with instruments and methods of formal thinking. Bush's view is that the mechanized ways of computation are complementary to human thinking. He wished instruments to 'approximately obey some simple law, and may be made to indicate the consequences of combinations of such relationships' (p. 647).

To begin with, Stibitz did not have a definite notion of a complete calculating device; it evolved and crystallized gradually as the work proceeded and throughout the construction of several successive models. In his 1940 memorandum, 'Computer', other than demonstrating the advantages of the binary technology of the telephone relays for calculating, the only reference to the properties of the device is this: 'It will be seen in these simple examples that there are numerous rules to be observed about the signs of the components and the ways in which the components must be combined. Computers working at such computations for long periods and high speed can hardly be blamed for making occasional slips.' To this

Stibitz adds: 'For some years, therefore, need has been felt for a computing machine which would relieve the operator of the numerous details involved in complex computations.' These passages show that in the view of Stibitz, the 'Complex Computer' to which he refers here is a sophisticated calculating machine that relieves the operator, the human computer, of the numerous details involved in complex numerical calculations. Only in retrospect did Stibitz and his associates at Bell become aware of their having had in their hands all along a multi-purpose device. Stibitz concludes his memorandum with the claim:

> 'One type of problem for which the computer has been found very useful is that of 'improving the roots' or a polynomial.... Furthermore, because of the inherent flexibility of switching equipment, it will be a comparatively simple matter to add many features of operation which experience with the present machine has shown to be desirable.'

Atanasoffargues in his memorandum (August 1940) that 'the main purpose of this paper is to present a description of a computing machine which has been designed principally for the solution of large systems of linear algebraic equations.' One of the considerations that motivated him to develop such a machine was the formulation of the general outline of a plan for mechanizing the process of successively eliminating one variable from a pair of equations. He adds that 'Computers rarely employ determinants in the solution of linear systems of equations; in fact, it is easy to show that the work is best organized in the old form.' Here, Atanasoff refers to human computers. Yet his memorandum is an expression of his struggle with a new conceptual grasp of computability. The aim is clear and definite: mechanizing the process of successive elimination of one unknown at a time 'in the old form', just as the human computers do it. What he emphasized is the application of binary technology, its crucial advantages, and its great superiority. However, Atanasoff does say: 'It is not the purpose of the writer to promote the general use of the base-two system of numbers but this would be perhaps feasible in a highly mechanized civilization.' One page further on, he says, 'Most base-ten computers have wheels... The analogs elements in base-two computers will be able to assume two positions.' Here the use of the term 'computer' clearly denotes a calculating device.

Schreyer, in a letter dated 15th October 1939, gives the following account on Zuse's device:

> 'The computing machine patented by Konrad Zuse differs from other machines principally in the following ways:

> 1) The number values put into the machine are translated into binary numbers (powers of 2) ... The execution of an operation in the binary system requires either mechanical or electrical relays...
> 2) The calculating operations for technical calculations are automatically carried out by the machine with the aid of a computing plan (which is read) and a store unit.'

Later on he adds:

> 'The machine is primarily intended for technical calculations. In an engineering department one could, for example, be able to calculate swiftly and accurately machine parts on a large or small scale (mechanical, electrical, etc.). The calculation of a part of different dimensions requires simply the insertion of the computing plan previously produced for this part with the new data. Thus, for the calculation, only one computing plan need be set up, which contains all the necessary formulae in coded form, that is, in a form which can be read by the machine. This can then be kept in an archive when not in use.'

Schreyer grasped the uniqueness of Zuse's machine in particular as a multi-purpose, accurate and high-speed calculating device, and by that he distinguished it from other calculating devices.

Zuse, in his patent application (11th April 1936), claims that

> 'The invention serves the purpose of automatic execution by a computer of frequently recurring computations, of arbitrary length and construction, consisting of an assembly of elementary arithmetic operations. The prerequisite for each type of calculation that is to be done is to prepare a computation plan in which the operations are listed serially indicating their type; and in which the numbers occurring in the course of the computation are numbered serially, or according to some other scheme ...'.

Zuse states that the vital components for such a device, based on binary technology, would comprise an arithmetic unit, a memory device, a selector mechanism (a control unit), an input device for the plan and an input-output device for data. This is a very close definition to the concept of the automatic program-controlled digital calculating machine, given in 1945 in the 'First Draft' of von Neumann.

Mauchly was the first to point out the importance of speed in calculations. In his August 1942 memorandum, he states,

> 'There are many sorts of mathematical problems which require calculations by formulas which can be readily be put in the form of iterative equations.

> Purely mechanical devices can be devised to expedite [this must be a typo in transcription] the work. However, a great gain in the speed of the calculation can be obtained if the devices which are used employ electronic means for the performance of calculation, because the speed of such devices can be made very much higher than that of any mechanical device. It is the purpose of this discussion to consider the speed of calculation and the advantages which may be obtained by the use of electronic circuits... it is to be expected that one of the chief fields of usefulness for an electronic computer would be found in the solution of differential equations.'

Mauchly points out additional advantages, other than the speed, compared to the differential analyzer, in particular in its accuracy, as he states:

> 'The mechanical analyzer has a limited accuracy, whereas the electronic device, operating solely on the principle of counting, can, without great difficulty, be made as accurate as required for any practical purpose.'

Mauchly's memorandum does not present any new approach or revolutionary grasp of a concept in calculating devices, but it serves as a demonstration, or rather invitation, for the application of new technology to calculating devices. Nevertheless, what is important here is that once the developers of ENIAC grasped the importance of its practical speed, they became aware that this speed created a new quality: the new high speeds in computing opened new possibilities in the design of these devices.

The notion of the universal machine capable of imitating or simulating the way of operation of the human computer or any other machine, was introduced for the first time in Turing's work 'On Computable Numbers' (1936). That work did not gain a great response on its initial publication, and its reading circle was most limited. In spite of being a theoretical mathematician, Turing occupied himself also with the practical design and construction of concrete devices during the war and even before its outbreak. In a report prepared for the National Physical Laboratories on the ACE, he expressed his unique and independent grasp of the notion of the computer in contrast to that of von Neumann and his disciples in the 'First Draft' and 'Trinity Paper' reports (though relating the First Draft solely to von Neumann is doubtful; see Appendix B). Turing had read the 'First Draft' and was even aided by it while composing his report on the ACE. Nevertheless, his ACE Report exhibits a different concept or notion of what a computer is. Turing had grasped, judging from the ACE Report, that the computer, first of all, was a device that was designated to obey a program. This greatly differed from the view of von Neumann of the computer as a device for the computation of numbers that can be defined in today's terms as a programmable calculator. In von Neumann's own words,

> 'Since the device is primarily a computer, it will have to perform the elementary operations of arithmetic most frequently.'

Turing expounded in his ACE Report on other possible applications such as puzzles, chess and other additional abstract and technical applications that I need not detail, as they are very familiar to today's computer users. The ACE Report had a minor influence on the development of computers in the UK and greater influence in the USA. The report gives a comprehensive account on the concept of what a computer is to be. Yet the influence of the ACE Report was much later and more gradual than that of the 'First Report'.

In a memorandum titled 'Intelligent Machinery' (1947), Turing points out (Turing 2004, pp. 395-432) that the memory of the machine determines, more than anything else, the complexity of its behavior. For Turing, the concept of the computer was anchored in minimal hardware, comprising memory, processor, and control. His concept of the computer is the widest given thus far. Its clear expression appears in full in his 1950 *Mind* paper, 'Computing Machinery and Intelligence'. Although he does not yet use for these devices the term 'Computer' in the title of the paper, but rather 'Computing Machinery', the paper is an extension of his 1947 paper, where the distinction and definition of the computer is clear and unequivocal:

> 'The idea behind digital computers may be explained by saying that these machines are intended to carry out any operations which could be done by human computer. The human computer is supposed to be following fixed rules; he has no authority to deviate from them in any detail... if we use the above explanation as a definition we shall be in danger of circularity of argument. We avoid this by giving an outline of means by which the desired effect is achieved. A digital computer can usually be regarded as consisting of three parts: store, executive unit and control.'

Without entering now into the ethics of the situation, von Neumann virtually determined the concept of the computer that has existed up until now. The 'First Draft' (the authorship and distribution of which, as I claim, was probably Goldstine's and not von Neumann's) reflected the grasp of the members of the ENIAC team of the future device to be constructed, the EDVAC itself, and was meant to incorporate all the ideas derived from the construction of ENIAC, summarized in the definition expressing the concept of the computer of the ENIAC team, including von Neumann:

> 'The considerations which follow deal with the structure of a 'very high speed automatic digital computing system', and in particular with a logical control... an 'automatic computing system' is a (usually highly composite) device, which can carry out instructions to perform calculations of a considerable order of complexity... it is worth noting, however, that the device will in general produce essentially more numerical material...'

Later on, an account is given on the essential and vital parts of such a system, which are the arithmetic calculating unit, logical control, a considerable memory and input-output mechanisms. Here also the analogies in terminology between terms borrowed from physiology, such as neurons and human brain cells, and the computer is set in writing for the first time. In ENIAC and in the 'First Draft', the issue of very high speeds for calculations is emphasized, in particular, in such devices as the automatic program-controlled digital calculating machines. The 'Trinity Paper' (1946), the 'Preliminary Discussion of the Logical Design of an Electronic Computer', can be viewed as an extension of the 'First Report', in particular as it is straightforwardly expressed in its opening line:

> 'In as much as the completed device will be a general purpose computing machine it should contain certain main organs relating to arithmetic, memory-storage control and connection with the human operator. It is intended that the machine be fully automatic in character....'

Here the term 'general-purpose' is used explicitly. In addition, the use of terminology borrowed from physiology, like the term 'organ', is exhibited throughout the report. The emphasis in the report is on the structure and design, or what is known today as von Neumann architecture, of the computer and the advantage which is provided by the use of binary notation for this type of device. Although the report belongs to a partial commitment in a contract between the Institute for Advanced Studies (IAS) of Princeton University and the US Army Ordnance Department, and was not published in any other form, it was nevertheless circulated by the IAS within the USA and abroad, just like the 'First Draft'.

This grasp of the definition of the computer, as designed by von Neumann (St. John) and his followers has been accepted in the main until today. It says that the computer is a digital serial/sequential device comprising four or five organs/units, as detailed in both the 'First Draft' and the 'Trinity Paper'. However, what has changed between von Neumann's days and today in the concept of the computer is the variety of practical applications of the computer. Since the 1960s, the notion of the computer has become increasingly tied to the meaning of an instrument for automatic processing of information/data. More recently, its notion has shifted gradually towards a more commonly accepted idea of a device for information manipulation, which is much closer to Turing's concept of the universal machine.

Summary

Until 1936, a clear distinction existed between equipment for arithmetical calculations and equipment for statistical and scientific calculations. The common terminology for the digital calculating means for arithmetical needs was the various 'calculating machines'. The equipment used for statistical and accounting calculations was termed tabulating or punch card equipment and bookkeeping equipment, respectively. This equipment related to the property of 'automatic', as expressed for example in the appellation 'Automatic Computing, Tabulating Recording Machines' [12].

The equipment for scientific calculations was, in the main, analog equipment, and the common terminology used for it was that of the various analyzers, such as differential, harmonic, integrator or the diversity of planimeters.

During the early 1930s, the few first attempts appeared for utilizing tabulating devices for scientific calculations in academic institutions [13].

The classification and distinction between regular calculating machines and automatic calculating machines began at the end of the 19th century. The distinction related to the motive power of the device or the method of deducing the multiplication results by a single operation by the human operator. Though such names as 'Universal Calculator' already appeared by 1874, such names probably designate calculating procedures and instructions for human calculators rather than any properties of any machine.

In France in 1933, Couffignal made one of the first clear distinctions between a regular calculating machine for commercial use and machines required for scientific applications [14]. Aiken, in his 1937 memorandum, stressed the differences in design and needs between calculating means for commercial use, like those of IBM, and those designed for purely scientific calculations.

From 1936 to 1946, each name or nickname for each of the various calculating devices denoted the unique properties and characters of whichever device as compared to other existing devices. From 1946 to the end of the 1950s, the terminology and the notion of the concepts of these devices began crystallizing into their current meanings. Still, one can find a variety of terms used in the names of these devices. However, the concept of the computer in its modern sense began to become institutionalized with the 'Trinity Paper' [15]. And so, various ideas came as synthesized into a new meaning that later became known as 'a computer'.

Since the 1960s, the distinction between the concepts of computers and calculating machines appeared as completely crystallized. Many institutions of higher education recognized and welcomed a new discipline, that of 'Computer Science' [16].

I conclude this section with the 1842 words of Ada Lovelace.

> 'The Analytical Engine does not occupy common ground with mere 'calculating machines'. It holds a position wholly its own... Thus not only the mental and material, but the theoretical and the practical in the mathematical world, are brought into more intimate and effective connection with each other. We are not aware of its being on record that anything partaking in the nature of what is so well designated the Analytical Engine has been hitherto proposed, or even thought of, as a practical possibility, any more than the idea of a thinking or of a reasoning machine.'

Ada Lovelace even considered the possibility of writing music by means of this machine! Lovelace and Leibniz were probably the first to grasp the concept of the computer, as in her vision of the Analytical Engine. Alan Turing thinking went the same way. He thought of the imitation of the functions of the human brain by artificial means and of the mechanical imitation of the order of operations in the same manner as the human computer. He hoped to imitate the results of the human brain's function by means differing from those of those of the human body. The character of the machine's reasoning is exhibited in its configurations and not its mode of operation. To envisage a computer in analogy with human thinking is transcendental, a transformation from notions associated with simple computing machine terminology into the very concept of the computer that is common today.

Norbert Wiener and von Neumann, who formed the Teleological Society at the beginning of 1945 and who strove for a synthesis of terminology and a transfer of concepts from brain physiology to the design of calculating devices, also sought to find analogies in the function of each. While Wiener used cybernetics had thus come very close to the concept of Turing, von Neumann, whose influence on the development of the modern computer was so crucial after 1945, viewed the computer mainly as a very sophisticated calculating device. And that was even despite the analogy and resemblance that he tried to exhibit in his writings such as his brilliant *The*

Computer and the Brain (1958). The difference between these two concepts of the computer is extreme, beyond compromise or reconciliation. Von Neumann, an applied mathematician who could perform incredibly complex calculations unaided by pencil and paper, needed a very high speed calculating device for very complex and particularly long calculations. He emphasized a particular logic of hardware in his design architecture, a logic that was meant to serve his pragmatic needs. The formalization in his device, in spite of the use of terminology borrowed from physiology, is identical to the use he made of his own brain, to perform and impress people around him with his unique manner of extremely rapid performance of calculations, and not an expression of a broader grasp of any computer concept of the likes of Turing or of Wiener. The concepts of Turing and Wiener that von Neumann brushed aside, emphasized the concept of artificial intelligence in the machine; that is to say, emphasizing the program, the software rather than the hardware.

Consciousness has recently risen among experts in the *milieu* of computer science as to what is known as 'von Neumann's bottleneck', the limitations of any sequential machine. It has inspired researchers to develop parallel machines, because of the need to overcome certain obstacles caused by the speed of operation of sequential machines towards applications to artificial intelligence. The main obstacle today in the application of these parallel computers is still that we do not yet have any precise notion of how to perform parallel programming. That would be a complete breakthrough in the concept of the computer. Some people are of the opinion that we are approaching the limits of digital computing, and that new analog-utilizing technologies will be the optimal solution for the future. These are fascinating speculation that well exceeds the scope of this study.

Notes

1] Webster's Dictionary, since 1646, has contained entries on 'Computer' and 'Calculator': 'Calculator—one who computes: a calculator, reckoner. Spec. a person employed to make calculations in an observatory, in surveying, etc.' Examples there relate to calculators of calendars or astronomical tables. Page 750 of the entry on 'Computer' ('calculator; one who calculates; a reckoner') includes several examples of usages of the word since 1380, in the sense of human computers or tables to aid in calculating as well as mechanical means for the execution of certain type of calculations, namely calculating machines. So, for instance, in William Thomson (1874) there is a title of 'The Universal Machine' and even earlier, in William Walton (1824), there is a heading of 'The Complete Calculator… and the Universal Ready Reckoner'. I surmise that the latter is a reference to a device that carries out the four basic arithmetic operations. Finally, page 28 of the 1876 Catalog of the

London Science Museum includes the line: 'This screw bears a calculator which serves to read angular displacement of less than 20 seconds.'

See F. L. Bauer, 'From Scientific Computation to Computer', in Zemanek (1972), pp. 57-71.

2] V. Bush, 'Instrumental Analysis', *Bull. American Math. Soc.*, vol. 42 (1936), pp. 649-669. Here is a survey of digital, analog and tabulating calculating devices, and a recommendation to adopt the digital principle for a control system.

3] F. L. Bauer, in Zemanek (1972), pp. 60-63.

4] N. Wiener, *Cybernetics* (eighth printing, Sept. 1975), p. 15. See also Goldstine (1972), p. 197. For a different view, see Heims (1982), pp. 185-186 and remark 16 on p. 468, where he claims that the meeting took place between 6 and 7 January 1945. In this meeting participated von Neumann, Wiener, Aiken, probably Goldstine and W. H. Pitts and W. S. McCulloch, the authors of the famous paper on the analogy between the binary system and the function of neurons: 'A Logical Calculus of the Ideas Immanent in Nervous Activity', *Bull of Math, Biophysics* 5 (1943).

5] Valtat (May 1936) and Couffignal (1936).

6] Aiken (1937) and Turing (1936).

7] Stibitz (1940).

8] Mauchly (1942).

9] The asterisk '*' in Diff. * indicates a footnote in which it is said that the Diff. stands for difference and not differential. Mauchly protested: he disliked the name of the device given in the title of the Diff. * analyzer report.

10] The IAS computers were built during the period 1950-1954. The EVIDAC and the GEORGE were constructed for the Atomic Commission's laboratory in Oregon, the ORACLE for the National Laboratory at Oak Ridge where the plant of the Manhattan Project for the separation of uranium was built, and the MANIC for Los Alamos. The University of Illinois' computers were the ILLAC and the ORDAC (1952). The National Bureau of Standards' computers, the SEAC and the SWAC, were built during 1950-1954.

11] Burks, Goldstine and von Neumann (1946).

12] The idea of automata was initially understood intuitively during the period in question; on it a whole theory of automata evolved. Regrettably, I overlook all this in the present study.

13] L. Comrie played a very important role in the introduction of commercial calculating means for scientific calculations in the UK. On similar activity in the USA, see G. W. Beahne, ed., *Practical Applications of the Punched Card Method in Colleges and Universities*, NY: Columbia University Press (1935).

14] L. Couffignal, '*Les Machines à Calculer, Leurs Principes, Leur Évolution*', Paris (1933).

15] See footnote 11 above.

16] P. J. Denning, 'The Science of Computing: What is Computer Science?', *American Scientist*, vol. 73 (Jan-Feb. 1985), pp. 16-19. I disagree with the contents of this article.

APPENDIX B

THE BORROWED FAME: THE ISSUE OF INTERNAL STORAGE IN THE ELECTRONIC COMPUTER AND BEYOND

> 'Who invented stored programming? Perhaps it does not matter much to anyone other than the principals involved just who gets the credit—we have the concept and it will surely stand as one of the great milestones in man's advances.'
>
> Paul Armer [1].

This Appendix discusses von Neumann's involvement in the development and in the writing of the history of the digital computer, as well as his and contribution to these. The introduction of the internal storage concept is one of the most fascinating and astounding events in the history of technology in general and the history of the computer in particular. The importance of this incident, as will be demonstrated, is in how it has stamped its imprint on the direction and trend of the design of computers on the one hand, and on the scope of computer development on the other hand. Indeed, the sheer scope of the aftermath of this incident exceeds the timeframe and geography of the present work, though nevertheless remains relevant, because it follows directly after the rest of the narrative to the very verge of conflagration, an aftermath that has not yet faded away even in our times, continuing to influence the historiography of computers [2].

The introduction of the concept of internal storage is rooted in the construction of the first electronic computer in the USA at the Moore School of Electrical Engineering, University of Pennsylvania (hereafter Moore), originating sometime in August 1942. It was called ENIAC, short for the Electronic Numerical Integrator and Calculator. The initiative for this project resulted from the publication of a Mauchly memorandum in August 1942, entitled 'The Use of High Speed Vacuum Tube for Calculating' [3]. Although the memorandum was written by Mauchly, it also reflects ideas that were crystallized with the aid of Eckert.

A climactic moment, for many, was the acrimonious falling out among the original ENIAC team on March 16, 1946. In 1934 a differential analyzer was constructed at Moore following a design by V. Bush at MIT. It was like the one designed and constructed at MIT. A twin of it was constructed for the US Army Proving Ground at Aberdeen MD, in the vicinity of Philadelphia. These analyzers were constructed almost for the sole purpose of deducing artillery ballistic firing tables by the US Army Ordnance Ballistic Research Laboratories (hereafter BRL). Eckert worked on the maintenance and improvement of that differential analyzer at Moore together with Mauchly, then an assistant professor at Moore.

Already by 1938, I. Travis, an instructor at Moore, was asked to check the feasibility of incorporating several desk calculating-machines to form one large scale calculating machine. Later on Travis and Brainerd, a professor and later on a dean at Moore, discussed the possibility of constructing such an electrical and electronic machine.

Mauchly was aware of Stibitz's work at Bell, following the Hanover meeting of September 1940. He also had some notion of the work of Aiken at Harvard. Mauchly visited Atanasoff at the University of Iowa at Ames in June 1941 and inspected the device constructed by Atanasoff and his assistant Berry. In one of his unpublished memorandums, 'Notes on Electrical Calculating Devices', Mauchly wrote on the distinction between 'analog' and 'impulse' (not continuous) devices, indicating that this terminology was of Atanasoff (see Atanasoff 1940). In the memorandum Mauchly presented his personal preference towards digital devices (a term then not yet used for these devices), but what is most intriguing is the discussion on the feasibility of an electronic calculating machine [4].

J. G. Brainerd, then the director of Moore, was well aware of the urgent need of ballistic calculations for the Army Ballistic Research Laboratories (BRL), as they asked him to deliver a more detailed written document to the BRL, based on Mauchly's work (August 1942) on the use of electronics for calculation [5]. Experienced and professional organizations and experts, such as the RCA, refused or declined to consider the idea or deemed this undertaking unfeasible. On April 9, 1943, the first official meeting as to the general prospects and feasibly to carry out such a project took place at BRL, Aberdeen MD. The Army decided then to go ahead with the project as an experiment and financed the project, to be carried out at Moore. The work on the project started at Moore on May 31, 1943; the contract between the Government and the University was signed on June 5, 1943. Before the outset of the work, a final meeting was held at Moore in which Colonel

Gillon of the BRL dubbed the new device 'ENIAC'. Then, by the idea of constructing the device it was intended to have over eight thousand tubes; it was constructed by a final design that required eighteen thousand tubes. To take a decision to go ahead with such a project in the face of opposition of experts and other professionals was courageous, in particular for those on the mathematical panel of the National Defense Research Committee (NDRC) [6].

The details of the PX contract (the code name provided for the project) are in the documents at Moore and at the deposit of the trial documents of the Honeywell vs. Sperry Rand case (1967-1974) at the Babbage Institute, Exhibits 1529 and 1532 (of June 4, 1943). The project began in earnest not before June 30, 1943, ending on December 31, 1943. The total sum of the budget was $61,700 (confirmation letter of accepting the contract, Exhibit 1529). The opening lines of the ENIAC contract itself, exhibit 1532, are:

> 'Fixed Price Development and Research Contract. Gentleman: The USA, acting through the undersigned contracting officer hereby accepts your company's offer on the terms stated in your proposal June 2 1943.'

The contract comprises twenty paragraphs, some of salient interest to the matter at hand: Paragraph VII concerns patent and royalties to be owned by the government, Paragraph XIII concerns secrecy and the nondisclosure of secrets, and Paragraph XX concerns reproduction rights.

According to the contract, the University of Pennsylvania was to supply the government copies of any report produced and, in case the project bore fruit at any stage, to transfer production rights to the government. The contract was changed many times as to the outline of the device and the additional requirements set by the Army. However, the principal paragraphs concern secrecy; those on patent rights and royalties remained unaltered. The last supplement to the contract dates November 16, 1946.

The total investment in the ENIAC project, as of 1945, reached the amount of $486,804.22.

On July 9, 1943 Herman Goldstine was officially appointed as Army Liaison Officer of the BRL for the ENIAC project. Before being called into military service, Goldstine was an assistant professor of mathematics at the University of Chicago. He got his PhD from the University of Chicago in 1936 and served as research assistant to Professor Gilbert A. Bliss (an expert and an authority on the mathematical theory of ballistics) between 1936 and 1939. Goldstine also taught a course on exterior ballistics. He was drafted at the beginning of 1942 and stationed at BRL on August 7, 1942, with the rank of sub-lieutenant. In September that year he was appointed on behalf of the BRL in charge of the Ballistic Calculating Center of the BRL located at the University of Pennsylvania [7]. Brainerd, then Director of Moore, was appointed to be in charge on the ENIAC project on behalf of the University. Eckert was appointed chief engineer and Mauchly was appointed chief adviser. The ENIAC team also included Sharpless, Chedaker, Arthur Burks and Alice, who was to become his wife, Harry Huskey, Adele Goldstine (Goldstine's first wife) and Kathleen Mauchly (Mauchly's second wife).

Two types of circuits were integrated into ENIAC. Circuits designated for the transfer of numerical data and circuits designed to carry control and instruction symbols. The device was intended to operate on what was known as the local programming principle, meaning, a complete manual reset of the connecting board was needed for the execution of a certain specific problem, in order that the data may flow from one unit of the device to another. This passage of data from one unit to another was possible for the sole purpose of execution, after obtaining a predetermined sign (asynchrony) for when the unit should start functioning and what type of operation or instruction it should perform. The program (sequence of functions) was determined according to input-output signs provided from the various units. Hence, the device was a parallel processing unit, executing several functions simultaneously; the design or setting of the hardware configurations for the execution of those parallel functions demanded that a few hundred manual operations be carried out, since each of the diverse units had its own function and object as well as its own set of instructions. The method of control for a specific unit rested on a sign or symbol provided by another unit. When that unit's sequence of operations came to an end, its output gave a sign to the next unit in tum to further process the interim result. The manual connections set on the switchboard was virtually redesigned each time anew and by a different model of the device according to the required task. Thus, ENIAC was originally a parallel device, insofar as each of the units could function independently and in parallel to execute its tasks and not serially as is common today.

The designers of ENIAC had considered the design, development and trial of the two special vacuum tube accumulators (registers for storage and calculating) as the decision junction for the continuation of the project. These basic electronic elements of ENIAC, intended for the execution of calculations and storage of data, were constructed of rings of ten vacuum tubes, each representing one decimal digit.

The two-accumulator experiment was carried out at the beginning of July 1944 and was a complete success. Brainerd and Harold Pender (then dean at Moore) reported these encouraging results to Goldstine by phone and in writing, while he was in hospital, as it happened. This timing is of crucial value, since it may help us resolve a certain dispute between the von Neumann-Goldstine faction (which included the Burks) and the Mauchly-Eckert faction.

The Goldstine-Burks faction claim that they 'vividly' remembered certain events, unsupported by written evidence: von Neumann had participated in the two-accumulator experiment and even offered his opinion on it; the others faction disagreed and claimed that von Neumann had visited the ENIAC project for the first time only after September 7, 1944. They base their claims on the documentation of the security pass, issued for the first time to von Neumann on that specific date. They argued that without such a pass he could not have visited the project. This pass appears among the exhibits of the Honeywell vs. Sperry trial. Yet, von Neumann's supporters bluntly dismiss this argument: von Neumann, who was such a prominent figure, did not require a security pass issued in advance in order to visit this classified project. However, as a matter of interest, among Aiken's papers at Harvard a telegram from von Neumann from Princeton, dated September 6, in which he informed them that he would come for a visit with Bergman on the morning of Friday September 8, 1944 (UAV. 298. 2005). Exhibit 2321, of August 15, 1944, a message from the Army's Ordnance Department to Goldstine, notified him of permission for von Neumann to visit the RCA; Exhibit 2287 of August 2 indicates that a pass giving von Neumann access to the RCA laboratories in Princeton between August 3 and September 3, 1944. Exhibit 2313 is probably the first written by Goldstine after returning from his sick leave and hospitalization.

Von Neumann and the ENIAC

Von Neumann's interest in computers, or more precisely in fast or high speed calculating means, was motivated by his direct involvement after September 1943 in the Manhattan-Project construction of the Uranium 235 bomb.

After von Neumann's return from the UK, he invites his student and follower Stanisław Ulam to join the project in a letter to Ulam (Exhibit 1676, September 25, 1943). In another letter to Ulam (Exhibit 1724, November 9, 1943), he says enthusiastically that the project is beyond any imagination, in need for serious mathematical work and is extremely secret.

In that project von Neumann was asked to calculate the shock waves created during an atomic explosion, which involved tremendously long and complicated calculations, although Norbert Wiener disagreed on this issue of calculations with von Neumann [8]. The calculations were concerned with the central problem of forming a critical mass in order to achieve an uncontrolled chain reaction, namely, a nuclear detonation. For this purpose, a technique was developed in order to bring sub-critical masses together in a very short duration to form one critical mass. The main problem, however, was how to compress them together rapidly and then keep them together for some time, forestalling their mutual repulsion during the initial stages of the process. Sustaining the process depended on it. Otherwise, the reaction would peter out. The technique utilized was a simultaneous thrusting of sub-critical masses of fissionable elements by means of explosives. The vital and dominant problem then was how to determine the most accurate timing for the shock wave of the explosives to obtain the desired result. So von Neumann was asked to find the solution to one of the most crucial problems essential for the success of the entire project.

At the beginning of 1944, von Neumann turned to W. Weaver, chairman of the mathematical panel of the NDRC, for help to track down some appropriate mechanized calculating means (Exhibit 1894 from 15th January 1944). Weaver directed von Neumann to George Stibitz, on loan from Bell Laboratories to the NDRC, in his capacity as an adviser helping to solve problems of fire direction and fire control [9]. On March 27, 1944, von Neumann wrote in a letter to Weaver: ‘Will write to Stibitz of my curiosity to learn more about the relay computation method, as my expectations concerning possibilities in this direction are much aroused.’ [10]. This seems to me strange. Von Neumann’s name appears on the list of the participants of the Hanover meeting of the American Mathematical Society in September 1940, in which N. Wiener and Mauchly also participated [11]. In addition to Bell-Stibitz’s ‘Complex Computer’, von Neumann was also aware of Mark I, Aiken’s device at Harvard that was electro-magnetic. This is uncontestable, as on April 14 he wrote that it was possible to mechanize the problem of shock decay and that he was in contact with Aiken. Indeed, von Neumann was negotiating with Aiken and the Navy until June 6, 1944, wishing to obtain permission for an arrangement to use Mark I for his own needs. incidentally, permission was granted: he was allowed to use Mark I for one day each week [12]. Additionally, since 1937, he had served as a paid adviser to the US Army in ballistics for the BRL. He was also a member of the NDRC.

The turning point occurred during summer 1944. The exact date of von Neumann joining the ENIAC project is in dispute, as argued above. It was at the railway station at Aberdeen that von Neumann and Goldstine met for the first time—by chance. This specific meeting led to a close, long-lasting cooperation and relationship between these two persons. It lasted until von Neumann's death in 1957. Goldstine developed a deep esteem for von Neumann that turned, step by step, into unlimited adoration and to the verge of idolization. It is thus advisable to treat anything written by Goldstine, on this issue in particular, with exceeding care, because Goldstine's glorification of von Neumann contributes to his own elevation too. The reader may very easily distinguish between von Neumann's 'sympathizers' who followed him to Princeton from Moore to construct computers for the Institute for Advance Studies (IAS), and those who went to or enjoyed the hospitality of the IAS in order to study the design and structure of computers. There are also many editors and authors of books on computers who copied sources closely linked with von Neumann, building up the myth and glorification of von Neumann's central role as a leading figure in the history of the computer, if not *the* leading figure.

In the historical meeting in the gloomy railway station at Aberdeen, Goldstine disclosed to von Neumann details of the development of the ENIAC and other events at Moore. He also invited him to visit. The document in which von Neumann's name is mentioned for the first time as participating in the ENIAC team meeting that I was able to trace is of September 13, 1944 (Exhibit 2421). It is a report written by Brainerd, of a meeting between them. Exhibit 2409 of September 10, 1944, that details the state of the ENIAC project up to that date has still no mention whatsoever of von Neumann. Without entering yet into details, then, I state here that all evidence suggests this: von Neumann became a special adviser to the ENIAC team only after the middle of September, 1944.

Goldstine (1972) devotes Chapter 6 of his book to von Neumann and the computer. According to the account that he made there, when von Neumann learned that Goldstine was involved in a project of an electronic device capable of executing 333 operations per second, the atmosphere changed immediately and von Neumann started interrogating Goldstine on it. As Goldstine reports it, the two traveled to Philadelphia soon afterwards so that von Neumann could see ENIAC. 'At this period the two accumulator tests were well underway' (p. 182). The ENIAC Log-Book, however, has no mention of a visit by von Neumann on the dates that fit Goldstine's story. Von Neumann's name likewise does not appear on the payroll of the project [13]. In Goldstine's story of both the case of this meeting and that of von

Neumann's involvement in the development of the internal storage concept (Chapters 6 and 7), as well as of anything concerning the dates related to these two events, there is no exact date and no reference to sufficient sources. Instead, Goldstine is somewhat vague: 'Sometime in the summer of 1944 after I was out of the hospital …' or 'Soon thereafter the two of us went to Philadelphia so that von Neumann could see the ENIAC' (p. 182). A few lines later he states, 'On 2 November 1944, my wife and I returned to Philadelphia ...' (p. 183), and

> 'This makes it quite clear to me that von Neumann had already visited the Moore School. My records indicate that I was back on duty after my illness around 24 July 1944 and that I probably took von Neumann for a visit to ENIAC on or about 7 August. I recall that von Neumann's first visit was during the two accumulator test. My travel orders show that my first business visit to Philadelphia after being released from the University of Pennsylvania Hospital was the first week of 1944.'

These accounts provide good background for what Goldstine wrote later on. Although he used to write very frequently, there is an abrupt gap in his records of his hospital stay; he resumed writing on August 11, 1944. Now he recalled vividly that on August 11 he wrote a memorandum (probably Exhibit 2313): 'Goldstine to Simon, Further Research and Development on ENIAC', in which he mentions some difficulties concerning the design of ENIAC, in particular the issue of its high speed storage capacity, which would cause 'considerable inconvenience and loss of time to the Laboratory in setting up new computing problems'. Goldstine claims that as a result of the August 11 memorandum, a committee meeting, known as the Firing Table Reviewing Board, was held on August 29, in which Goldstine's requests were backed. The minutes of that meeting indicate that von Neumann was present there (p. 185, footnote 5, memorandum C. B. Morrey to L. E. Simon, August 30, 1944).

This is the way Goldstine 'reconstructed' (almost by the method of mathematical elimination) the date of von Neumann's first visit of ENIAC on August 7, 1944 [14].

Von Neumann's correspondence with Ulam and with others led to different conclusions. He informed everyone that he was going or had already gone west (probably to Los Alamos) during between July 3 and 25, 1944. Ulam (1976) corroborates this.

The security clearance from the military authorities was issued for von Neumann and an additional mathematician, James Alexander, to visit

ENIAC on September 5, 1944, and for the duration of two months, beginning on September 7 (Exhibit 2401). As indicated above, since his return from the west, von Neumann had visited other places as well, such as RCA and Aiken at Harvard. Goldstine and Burks declare that von Neumann had a general security pass, granting him access to visit ENIAC with no specific permission. If so, then why did he apply for a permit to visit ENIAC? Why did he take the bother? I assume that the security people knew exactly what type of security clearance von Neumann possessed, and would hardly bother to issue a redundant permit. Indeed, von Neumann needed a security clearance permit not only to visit ENIAC, but also to visit the RCA laboratories at Princeton and Aiken's laboratory at Harvard. This he was granted on August 2, 1942. In that time a lot of suspicion prevailed between the various groups of developers, and the coordination of a visit in such places was not as simple as the way Goldstine suggests. During my discussion with Burks at Ann Arbor on October 12, 1986, he noted my skepticism about the claims of the date of von Neumann's visit to ENIAC. Sadly, he asked me: 'You don't believe me that von Neumann's first visit was during the two accumulators test?' I answered, 'To me this issue is debatable; it is you and Goldstine who have to provide more substantial evidence, including sources to refute the Mauchly-Eckert claim. However, from the evidence I have collected, during the two accumulators test Goldstine was in hospital, and there is a difficulty in coordinating the various dates. Moreover, it even seems that von Neumann was then on the West Coast.' It seems to me that if the confusion created by Goldstine and the Burks is unintentional, then it may derive from relating events outside the ENIAC project in which von Neumann participated as part of his other duties and obligations, like the meeting he participated in on August 29, and to relate them in all good faith to ENIAC in retrospect. Indeed, during that period, several development projects in electro-magnetic and electronic technologies and ideas linked with calculating devices for fire control and the deduction of ballistic firing tables were in progress and under discussion by the NDRC and other authorities. Stibitz and others were of the opinion that it would be much faster and cheaper to design and construct devices based on electro-magnetic relays.

People like Stibitz, Aiken and in particular V. Bush were probably influenced by the everyday needs of the war and adopted a pragmatic attitude to encourage and invest in success—in what has been already successful and proved itself, and not to waste effort in trying to apply risky new technologies when the old ones accrue the same results. But this too is controversial, because Bush had supported new and advanced projects and he himself had headed the Manhattan Project at its outset. It is also possible that this dispute has something to do with financial considerations. However, that controversy only came to a decisive end by 1949, so for our present purpose what has been said so far should suffice.

A letter written by Mauchly and Eckert of August 31, 1944, provides an account of the possibility to utilize the mercury acoustic delay line method as a means of storage, thereby increasing both speed and storage capacity. This letter was delivered by Brainerd to Goldstine on August 31, 1944 [15]. A final report containing seven handwritten pages in all, probably written by Eckert, of June 28, 1944 (Exhibit 1570), pertaining to the use of the mercury delay line method as a storage means. Eckert tried to develop such a means before the enhancement of the ENIAC project for RADAR, according to the contract signed between the Moore School and MIT.

In discord with this, Goldstine argues that

> 'By the end of August 1944 he was urging the development of a new electronic computing device that would:
>
> A. Contain many fewer tubes than the present machine and become more practical.
> B. Be capable of handling many types of problems not easily adaptable to the present ENIAC.
> C. Be capable of storing cheaply and at high speeds large quantities of numerical data.
> D. Be of such character that the setting up on it of new problems will require very little time.
> E. Be smaller in size than the present ENIAC.' [16].

In our discussion, Goldstine argued that this memorandum rested on conversations he had already held with von Neumarm.

Brainerd, in a memorandum of September 13, 1944, already suggested proceeding with research on a new device, the EDVAC—the 'Electronic Discrete Variable Calculator'. That letter contained cost and time estimates for the research and development work involved. The total proposed expenditure was $105,000, with full scale work to begin on January 1, 1945, with work 'on a small scale [to begin] on October 1, 1944', which would proceed for one year [17]. This document names von Neumann for the first time—as participating in a meeting on the ENIAC project. The first Research and Development Order on the EDVAC was issued by the BRL on September 18, 1944. The contract was signed for nine months and the date for beginning the work on it was January 1, 1945 [18]. Details on the

EDVAC are in J. P. Eckert, Jr., J. W. Mauchly, and S. R. Warren's 'PY Summary Report No. 1' of March 31, 1945, that says,

> 'The problems of logical control have been analyzed by means of informal discussions between Dr. John von Neumann… Dr., Mauchly, Mr. Eckert, Dr. Burks, Capt. Goldstine and others… Points which have been considered during these discussions are flexibility of the use of the EDVAC, storage capacity, computing speed, storing speed, the coding of problems, and circuit design. These items have received particular attention … Dr. von Neumann plans to submit within the next few weeks a summary of these analyses of the logical control of the EDVAC together with examples showing how certain problems can be set up.' [19].

The codename 'PY' in the title of this document refers to the Moore School's accounting symbol for the EDVAC; the codename 'PX' there refers to ENIAC (Goldstine 1972, p. 187, note 8). A secondary report by the same authors, the 'PY Summary Report No. 2', of July 10, 1945, says,

> 'discussions have been held at regular intervals at the Moore School to develop a logical plan for the EDVAC ... Dr. John von Neumann ... has prepared a preliminary draft in which he has organized the subject matter of these discussions. This material has been mimeographed and bound. It consists of a 101-page report entitled "First Draft of a Report on the EDVAC by John von Neumann".'

(See also Goldstine 1972, pp. 187-188). I have some doubts as to the authorship of the 'First Draft' by von Neumann and discussed this issue in depth with Goldstine in our meeting on October 22, 1986, which I tape recorded with Dr. Goldstine's permission. I raised in that discussion the possibility that the author of the draft was not von Neumann but Goldstine, since at that particular time von Neumann was in Los Alamos. Goldstine first replied that he had only edited it. When I observed that the style of the 'First Draft' is not von Neumann's but Goldstine's, he replied evasively, 'So you may conclude'. I shall not elaborate on this here.

The 'First Draft' was first published in 72 copies, despite the security regulations pertaining to the ENIAC project that strictly restricted circulation to five copies only (of which two copies were intended for the military history archive) of any document related to ENIAC. When I asked Goldstine on whose authority these 72 copies were published and who violated the security regulations, he replied: 'It was my decision and under my authority'. Eckert and Mauchly promptly reacted to this 'First Draft' with their own report of September 30, 1945, 'Automatic High Speed Computing: A Progress Report on EDVAC'. In that report they tried to balance the impression created by the 'First Draft' as to the esteem and credit given to von Neumann thereby and his contribution. The report says,

> 'In January, 1944 a "magnetic calculating machine" was disclosed ... an important feature of this device was that operating instructions and functions tables would be stored in exactly the same sort of memory device as that used for numbers... The invention of the acoustic delay line by Eckert and Mauchly early in 1944 provided a way of obtaining large high speed storage capacity that, when work on it permitted, the development and construction of such a machine should be undertaken. This machine has come to be known as EDVAC (Elec. Discrete Variable Computer) ... During the later part of 1944, and continuing to the present time, Dr. John von Neumann, consultant to the BRL, has fortunately been available for consultations. He has contributed to many discussions on the logical controls of the EDVAC, has prepared certain instruction codes, and has tested these proposed systems by writing out the coded instructions for specific problems. Dr. John von Neumann has also written a preliminary report in which most of results of earlier discussions are summarized.' [20].

To the claim that von Neumann did not give credit to other members of the ENIAC team in the 'First Draft', Goldstine replied,

> 'The reason for this was that the document was intended by John von Neumann as a working paper for use in clarifying and coordinating the thinking of the group and was not meant for publication.' [21].

If this is the case, then why were 72 copies prepared? And why were they distributed to members of the ENIAC team? Goldstine claims that on June 25, 1945, copies were given to 24 persons closely connected to the project. However, the importance of the document was so clear that later, as its fame grew, many outsiders requested copies from the Moore School through Goldstine, who gave them willingly. Goldstine concluded,

> 'Through no fault of von Neumann's, the draft was never revised into what he would have considered a report for publication. Indeed, not until several years later did he know that it had been widely distributed.' [22].

Evidently, Goldstine did not provide adequate credible answers to the questions posed on the authorship and the circulation of the 'First Draft'. This seems to me to corroborate the claim that von Neumann was not the author of the 'First Draft'; he probably consented to its content—either before its publication by mail or, as Goldstine claims, in his purported capacity merely as editor, from Los Alamos. Possibly he consented to its content only in retrospect. That is, possibly von Neumann was dragged into this impropriety of Goldstine only unintentionally.

Harry D. Huskey, an original member of the ENIAC team who wrote the ENIAC's operational manual, claims that when he worked with others on the logical design of the ACE (a computer that Turing designed at the end of 1945) at the National Physical Laboratory in London, in spring 1946,

> 'We understood logical and-or circuits since these had been used in ENIAC, and with Eckert's mercury delay line storage we knew that data and instructions could be stored together.' [23].

Huskey adds that he had not found anything new in von Neumann's 'First Draft'. He continues,

> 'I feel that several of us on the Moore School team could have written a sample stored program if felt necessary... This in no way detracts from John von Neumann's ability to recognize the importance of an idea, and to develop such concepts at the rates that the rest of us could only admire as spectators at a race. Also John von Neumann's documentation of ideas was of tremendous value in disseminating the concepts.' [24].

N. Metropolis and J. Worlton (Metropolis, together with Stanley Frankel, had the honor of running the first problem on ENIAC during November-December 1945, on the Los Alamos problem in which von Neumann too was involved) claim that the Mauchly-Eckert's report of September 1945 had made him aware that the concept of internal storage existed at the Moore School well before von Neumann joined the ENIAC project as a consultant and well before EDVAC was designed. Metropolis may have had also personal knowledge of this, as he joined the ENIAC project as a programmer very close to the publication of the 'First Draft'. Metropolis and Worlton add that the fame that von Neumann had gained for this basic concept derives from the 'First Draft' that had summed up all the work that had been invested earlier in the design of the EDVAC, including the concept of internal storage. They say,

> 'John von Neumann contributed significantly to the 'development' of this concept, but to credit him with its invention is an historical error.' [25].

By way of clarification, let me add that astonishment with the ENIAC's speed of operation led to its nickname 'MANIAC'. That name was also given to a device developed under Metropolis' guidance for the Los Alamos laboratory (see Eckert 1976, p. 65), although the two machines are quite different.

Is It Really All About Internal Storage?

What is actually the problem of internal storage? And why is it so?

A basic organizational principle is the ‘reverse salient’ idea (T. P. Hughes, 1975), or the ‘bottleneck’; I call it the ‘limiting factor’: it disrupts the harmony of an operating system, since no system will ever run faster than its slowest component. ENIAC employed several integrated components or units that operated in combination. As they utilized vastly different technologies, a great gap of operational and reaction speed between them became inevitable. Its calculating and storage accumulators operated with enormous speed on the electronic technology of vacuum tubes for numerical data, whereas the logic control unit functioned on the slow technology of punch cards and electro-magnets. To harmonize them, internal storage was introduced: that numerical data and instructions should be stored and operated on in the same manner; the instructions and the numbers were stored in the same high speed memory and treated as identical symbols and as parts of the same program. This required a larger storage capacity. It also required a high speed electronic control unit capable of distinguishing between numerical data and instructions. Such internal storage rested on an abstract idea that demanded an innovation in control and storage. The need to increase the storage capacity was met by Eckert and Mauchly by their construction of a mercury delay line. Briefly, they utilized the piezoelectric (derived from the Greek *‘piezein’*, ‘to press’) effect in a crystal—any mechanical change in the shape of a suitably cut crystal creates an electric charge in it and, conversely, an electrical charge in a crystal causes a mechanical change in it. This way electrical signals transform into mechanical signals and *vice versa*. The mercury delay line idea rests on the transmission of an electrical signal through mercury (though it could be any other conducting fluid), where it is delayed by its transformation into an ultrasonic signal and then back into an electrical one. The addition of piezoelectric crystals on both ends of a container obtains a pre-assigned time delay that represents the desired storage effect.

The imbalance between the storage of numerical data and the storage of alphanumeric instructions limited the performance of ENIAC. Internal storage opened new options for the operation of the device in that, in turn, it opened new possibilities in programming. This is how computer science scholars evaluate the announcement of ‘internal storage’. And that is precisely what von Neumann did; he (or Goldstine on his behalf) announced the advent of internal storage and gave it a definition and structural formalization, as a starting point for the modem computer era.

And yet, what happened is much more interesting. We see here two parallel approaches. Technicians clearly perceived the technical deficiencies of ENIAC. The problem of the uneven speeds of the various units was clear already in the early stages. That it was possible to adopt electronic technology to the control unit and the instructions was evident. However, the question of whether the concept that the instructions and numerical data were identical in Turing's sense is not yet clear. A question remains open and is to be discussed and resolved, if possible, later on. It is this. What was meant by the concept of internal storage by the ENIAC team before von Neumann joined the project? Answer: the use of two identical high speed memories, one for instructions and the other for numerical data, or the use of only a single memory for both. No more, no less.

The Eagerness to Unveil ENIAC

The 'First Draft' aroused a bitter controversy within the ENIAC team, as to the credit due for the contributions made by its members, their legal rights and prestige, especially in consideration of their influence on the subsequent EDVAC project, and direct influence on the history of computers in general. This controversy was initially pleasant and collegial, but later on it grew into an open conflict in which two hostile factions formed. The principal driver of the conflict seems to have been, and remains, ego involvement, the craving of some members of the ENIAC team for recognition and credit as developers, pioneers or independent inventors of some of the ideas incorporated in ENIAC. Eventually, this controversy turned a litigation, reaching its peak during almost eight years of court process (1967-1974), in which, in addition to patent royalties by commercial firms, the craving for recognition as inventors, prestige of the co-inventors of ENIAC dominated the controversy once more.

Warren Weaver, chairman of Section 2 (later on Division 7) of the NDRC, who was in charge of the development of calculating and fire control means (and later became chairman of the mathematical panel of the NDRC in 1942), asked von Neumann to write a report on calculating devices, including ENIAC and EDVAC, in 'Proposed NDRC Report on Computing Devices'. Weaver intended to circulate this report in 'the scientific community' (a somewhat fuzzy term). Since ENIAC and EDVAC projects were classified as confidential, it was necessary to declassify them. Weaver wrote to the BRL on this matter on March 8, 1945 [26]. The director of the

BRL, Colonel L. Simon, was ready to grant such permission pending the approval of the Patent Branch of the US Army Ordnance Department. Goldstine intervened, recommending acceptance of Weaver's request to include ENIAC and EDVAC in von Neumann's report: 'The NDRC report mentioned is basic communication and is highly desirable at the present time, and it is further very desirable that ENIAC and EDVAC machines be included.' [27]. On May 8, 1945, Weaver obtained final permission, enabling von Neumann to include ENIAC and EDVAC in his lecture—on the condition that the level of security classification of the lecture would be 'restricted' and that it was given only before a closed audience of the Applied Mathematics Panel. Von Neumann never completed such a report for the NDRC [28].

With the preparations to reduce the security classification level of ENIAC to permit the restricted publication of the report, the ENIAC team discussed the question, who should be the signatories of the part of the report related to ENIAC and the EDVAC. This discussion indicates a significant mistrust within the ENIAC team. The mistrust was particularly between Mauchly and Eckert on one side and von Neumann and Goldstine on the other. They reached compromise; the authors of the report should be Mauchly, Eckert, Brainerd and Goldstine. [29].

Goldstine claims that he and Colonel Simon, the director of the BRL,

> 'were eager for information of these machines to reach the scientific community as soon as possible, since we realized the great significance these devices would have. We therefore did all in our power to lower the classification of the projects and to encourage von Neumann to write his report. As a matter of fact, so well had the word on the ENIAC and EDVAC project "leaked" to the scientific community that the number of visitors both domestic and foreign had reached proportions that there was concern about the delays these visits were causing.' [30].

To block this trend, Goldstine says,

> 'On 26 June 1945, I informed Dean Pender that no further clearances would be granted to visit the ENIAC… This policy was not very actively carried out, but it did serve to keep down the numbers of visitors to some extent' [ibid.].

Was the project declassified or was the number of visitors reduced? I asked Goldstine why he was so eager to inform the public about ENIAC. He replied,

> 'I and Gillon, who was in charge of the project in the Chief of Ordnance, wanted to show what the money was used for and to raise the prestige of the Army.'

Goldstine argued that the minutes of the 'Meeting on Computing Methods and Devices at Ballistic Research Laboratories, 15 October 1945', made it clear that the wish to inform the public about ENIAC linked with a 'desire at this time on the part of the leaders there to make their work widely available'. He did not indicate either who those 'leaders' were or their kind of leadership. Admittedly,

> 'It was accordingly proposed that as soon as ENIAC was successfully working, its logical and operational characteristics be completely declassified and sufficient publicity be given to the machine ... that those who are interested ... will be allowed to know all details...' (Goldstine, 1972, p. 217).

Yet a letter from the Soviet commercial mission in Washington to the University of Pennsylvania requesting information met with no reply [31]. Still, ENIAC did become public knowledge. A subcommittee of the magazine *Mathematical Tables and other Aids to Computation* that represented scholars in the field in the USA and the UK, under the leadership of its editor, R. C. Archibald of the University of Chicago, initiated a conference on calculating devices at MIT on 29-31 October 1945, advertised as the National Research Council Program Conference on Advanced Computation Techniques. This conference was partially intended to inaugurate Bush's new analyzer at MIT. Brainerd, now Dean of Moore, wanted talk at the conference on ENIAC and EDVAC. Permission for such a talk was granted. It was promised that it would be a closed meeting and attendance by invitation only, without publication or advertisement. Brainerd, Eckert and Mauchly appeared at the conference as representatives of Moore School, and Goldstine and von Neumann as representatives of the government [32]. Permission was granted in principle to attend and lecture at the MIT conference, and the official clearance to change the classification of ENIAC from confidential to restricted was issued only on September 17, 1945 [33]. A public release of ENIAC was planned in two phases: first a briefing of the representatives of the press on February 1, 1946, and then a public presentation on February 15, 1946 [34].

The Issue of the ENIAC Patent

Goldstine (1972, p. 221) asserted, 'The problem of patents on ENIAC and then a little later on the EDVAC was to have an explosive impact on the

University of Pennsylvania'. On this point I quite agree with him. According to the framework of the ENIAC contract between the Army and the University of Pennsylvania, the university had two options for the application of patents arising from inventions made during the term of the contract that are also detailed in a letter dated December 23, 1944, from the Head of the Patent Branch at the US Army's Office of the Chief of Ordnance, Colonel E. H. Herrstrom, to Dean Pender, 'Patent Application on ENIAC': a) the university could apply independently for a patent and permit the government various royalty free licenses; b) the government would take over the task of issuing the patent as a contractor for the university. In either option, 'Title of the inventions will remain the inventors and an appropriate license to the government will be executed.' [35].

The issue of the patent and the eagerness to make ENIAC public together created mounting tensions within the ENIAC team by March 1945. The acting forces were Goldstine and Colonel Gillon (BRL), with regard to its public release. Goldstine told me that he used to work directly with Colonel Gillon in the Office of the Chief of Ordnance, thereby bypassing Colonel Simon, Goldstine's direct superior, because in Goldstine's opinion 'Simon was too conservative, while Gillon was open-minded'. Goldstine had thus much power over the project, far beyond his rank of a lieutenant. Mauchly and Eckert who to delay public release of ENIAC until the preparation and application for the patent was over. The university authorities were evidently split. Brainerd, in charge of the project, and Pender, then the Dean of Moore, took it for granted that the patent belonged to the university. The stand of George W. McClelland, the President of the University, was unclear [36]. Mauchly and Eckert disagreed with von Neumann on the design of the EDVAC. In both cases Goldstine stood firmly on the side of von Neumann. Goldstine stated that Mauchly and Eckert had positioned themselves as the sole inventors and developers of all the ideas and concepts of EDVAC, a view that 'was strenuously opposed to John von Neumann and me.' [37].

In a meeting held in Washington in March 1946 between the rival claimants, in which representatives of the Ordnance Department also participated, von Neumann submitted evidence that he had contributed three ideas to EDVAC, worded by his lawyers thus: '1. A new code for enabling the operation of the EDVAC. 2. The serial performance or progression through the system of the various arithmetical operations required for the solution of the whole program. 3. The use of the 'iconoscope…' [38]. Mauchly and Eckert had requested in writing all the members of the ENIAC team, von Neumann included, to present their claims for patent rights, if any. Burks, for example, responded immediately on September 27, 1944. Burks proffered a handwritten response bearing no date, stating: 'I have no such claims at present.' There is also a handwritten note by T. K. Sharpless, who responded with several letters. A letter of March 4, 1946, says, 'Dear Pres. … I mentioned to you previously in a letter that I felt that I had some interest in the mercury line, namely, in the business of polishing the crystal... In addition, under item t of "Outline of Patent Application Material" is a note about clearing counters to selected points by gating from a state of ring, as in multiplier program ring. This too I believe is my idea. I am writing this not in the spirit of annoyance but rather in the hope that the engineer on both the PX and PY may soon have a meeting to discuss ways and means of definitely establishing patent rights and doing something about the oft mentioned patent pool. If you want to talk these matters over with me personally I shall be very happy.' Since he did not receive a reply from Eckert, he wrote another note on March 10, 1947:

> 'In reply to a letter from J. P. E. Jr. [Eckert; A. A.] of 27 Sep. '44 I wrote saying in effect that I felt that I had certain interests in the patents which might arise from work on PY or PX. I stated that I could make no definite claims until specific patent applications were made out.. I received no written reply on my letter of March 4, 1946.' (Defendant Exhibits 29 and 39 of Affidavit of Arthur W. Burks).

After considerable acrimony and tension, an additional meeting was held between the parties involved on April 8, 1947, to try to resolve the problem relating to EDVAC. The 'time bomb' of that meeting was the claim of the Legal Branch of the Ordnance Department that the circulation of the 'First Draft' by von Neumarm was to be treated as a publication in a strict legal sense, thereby placing the EDVAC report in the public domain. Consequently, the lawyers of the Ordnance Department withdrew from the task of preparing patents on the EDVAC work on behalf of Eckert and Mauchly. Only von Neumann retained his own legal representation, and after some acrimony he finally asked to leave before the meeting began. Goldstine says,

> 'At the meeting von Neunann and I proposed sorting out those ideas which could be attributed to specific people and agreeing to joint patents on the balance. But no agreement could be reached...' [39].

Goldstine also claims,

> 'Most of the universities in this era were quite naive about business matters, and the University of Pennsylvania was no exception... The University of Pennsylvania had in those days a vague policy of permitting each employee

> who requested it all rights to his invention. This was not an automatic procedure and required a petition by the employee to the Board of Trustees.. All were working to help defeat the enemies of the United States. They had put all patent considerations very much into the background.'

I disagree: there was a clear policy at the University as to patent applications (more on this below). So I conclude this section with the following passage from Goldstine:

> 'Anyone in the project, who had worked for Eckert and Mauchly, even though they might have contributed to the program in general, were probably not entitled to patents since the custom was that the originator of an idea usually holds all patentable ideas which might originate in the group working under him.' [40].

To reiterate, among the Honeywell vs. Sperry Rand exhibits, there is a document—Exhibit 1350, 'Academic Custom on Inventions and Discovery'; University of Penn., page 376—that refers to the University of Pennsylvania's official policy at that period. It refutes Goldstine's claims. It states very clearly and unequivocally that all inventions, besides those concerned with public health such as drugs, medical instruments and medical processes, may be patented, pending a permission from the President of the University, with all expenses borne by its applicant.

Von Neumann and his Connections with the Establishment

Steven Heims (1982), *John Von Neumann and Norbert Wiener: from mathematics to the technologies of life and death,* is excellent. It describes the fascinating system of relations between von Neumann and the business establishment in general, and that of the defense and military establishment in particular [41]. Von Neumann's relations with Lewis Strauss are a key to von Neumann's source of power. Heims offers a deep, critical and political analysis of the network of his relationships, based on a certain structure of national security, of which von Neumann, together with V. Bush and E. Taller, formed the science and technology side, and President Truman and Admiral Strauss and the Chiefs of the General Staff formed the government side. According to Heims, for every tool and idea that von Neumann discussed, he always emphasized its possible military applications and the implications it had for the international balance of power—in order to win the favor of the military [42].

The mathematician Stanisław Ulam, one of Von Neumann's best friends, described his attraction to the high ranks and their power [43]. Heims reports that von Neumann served as a consultant and adviser under payment to twenty-one different bodies and organizations at once. In 1944, in addition to being a consultant to the BRL and the US Navy Ordnance Department, he was also a mathematical adviser to the Manhattan Project. Von Neumann was asked to join the project by Oppenheimer in September 1943. Von Neumann soon became effectively a personal consultant to General Leslie Graves, the military commander of Los Alamos and the director of the Manhattan Project. Bush was in charge of the project on behalf of the NDRC, and Oppenheimer in charge of the science. Von Neumann cultivated ties and influence with those connected with technological military planning, consistently obtaining appointments as a technical adviser or any other type of consultancy [44]. He had a unique talent in forming public and human relations. This quality derived from the high esteem and prestige that he cultivated in certain influential circles or with top brass, combined with perfect timing in time and place [45]. As a banker's son, he was used to interest in money and in material reward; he saw to it that he was always paid well. In addition to his various occupations, he was a well paid consultant to oil and steel companies, IBM, etc. He knew how to integrate himself as a consultant. He was remarkably persuasive with all who surrounded him. His motto could have been 'I influence; therefore, I am' [46]. His comprehension of power was second to none. He possessed a rare synthesis of intellectual power with practical day-to-day technical ability, which he shared with the likes of Babbage and Turing. Von Neumann was considered as one the quickest minds in of his era in data processing. He was equally well known for his incomparable working ability and long hours. In his notebook, as well as in those of Mauchly, I found a table of entries of sleeping hours for each night. The government and security establishments needed him at their side. In the period 1945-1955, a person of von Neumann's scale and caliber was a great political asset because at that time most of the influential academic establishment went against the integration of science for military use and wanted to cut the financial ties of research with the government, especially with the military, in order to retain academic freedom and financial independence. Von Neumann never joined any group that opposed nuclear research and never signed any of the various petitions against the expanding powers of the Establishment. In one case he did sign such a petition, and he soon withdrew his signature. His rationalization was, 'he does not deal with politics only with technical problems' [47].

To Whom Belongs the Glory?

How was it that a man of such scientific eminence and reputation as von Neumann, who richly deserved the praise for inventions, patents and scientific achievements, allowed himself to occupy such an embarrassing position in one of the most crucial events in the history of digital computing? The issue of internal storage, reverberating in controversy even after his untimely death in 1957, is unabated even today. This drama provided unprecedented glory and fame to von Neumann as the sole thinker and inventor of the internal storage in particular and of the modem computer in general. The publication of the 'Trinity Paper' [48] led to the robbery of a group of inventors and developers of their rightful credit and privileges. My study has led me to conclude the following.

a) The idea of the internal storage is not directly linked with von Neumann. It was crystallized by most of the designers of automatic program-controlled digital calculating machines in the period of 1935-1945. For example, in the UK, Turing included the concept of internal storage in his Universal Machine, as he implemented it in the design of the Colossus. It was also crystallized in Germany by Zuse in 1941 [49]. The ENIAC team, before von Neumann joined it, were aware of it. Yet, due to the advancing stages in the construction of ENIAC, they delayed its implementation in ENIAC and decided to incorporate any new ideas into the next model, the EDVAC, as they did.

b) As to additional characterizations of automatic program-controlled digital calculating machines mentioned in von Neumann's two reports—the 'First Draft' and the 'Trinity Paper'—the binary notation and the parallel computation was nothing new, for the ENIAC team or for developers of such devices elsewhere. A short survey or even a glance at the history of the computer provides ample evidence that there was nothing new in the idea of binary notation in the 1930s, and that many devices utilized and operated on it in Germany, France, the UK, the USA and even Japan. Thus, for example, Turing had constructed a binary multiplier even while at Princeton in 1937, right under von Neumann's nose. The devices of Zuse, Atanasoff and Stibitz all operated on binary technology and notation, not to mention the papers published by Couffignal and Valtat and the British developer Phillips in 1936, all of which deal with the application of binary notation for calculating devices.

Are the publications of those two papers by von Neumann (Burks and Goldstine, the co-authors, should be considered in this case as under the command of von Neumann) to be considered as the result of, or byproduct derived from, wickedness, innocence or plagiarism? My answer to this is that we witness here a phenomenon of a person driven by both a confluence and conflict of interests: von Neumann as a consultant to the BRL and to the Army and von Neumann as a scientist, as a member of the ENIAC team. The exact date when von Neumann began to participate in the project as a member of the ENIAC team remains in dispute; it falls between August 7 and September 7, 1944. On August 2 he visited the RCA laboratory at Princeton and stayed at Princeton between August 3 and September 3, 1944 (according to Exhibit 2287). Goldstine was hospitalized during the two accumulator tests, and the report of Pender to Goldstine on them is of July 3, 1944 (Exhibit 2218, 1). The first letter I have traced after Goldstine recovered is of August 11, 1944 (Exhibit 2313). Goldstine was a prolific letter writer who responded to his mail as soon as he could and the speed of mail delivery in those days was impressive: usually, letters reached their destination within 24 hours. In a letter from the Ordnance Office to Goldstine of August 15, 1944 contains a security pass for von Neumann to visit the RCA (Exhibit 2321). Compare this with the pass for von Neumann's visit of ENIAC which was granted on September 5, 1944, taking effect on September 7 for two months only (Exhibit 2401). The first mention of Von Neumann's having attended a meeting involving ENIAC is in Brainerd's letter to Colonel Gillon of September 13, 1944 (Exhibit 2421).

Von Neumann had shared ideas and developments that crystallized in discussions of the ENIAC team; he contributed his own ideas while absorbing ideas of others. As consultant to the Army (since 1937), he could spot and name quickly the properties of calculating devices that were being crystallized during the long debates of the ENIAC team. There was an obvious conflict of interests between his functions as a consultant to organizations in two different domains (the BRL and the Army), that sowed confusion. Therefore, consciously or not, the 'First Draft' synthesizes both functions. That report serves as a summing up of the state of art technology up to the time of its writing, with regard to the development of electronic automatic program-controlled digital calculating devices, while it also served as a 'technical, logical specification' or standard for eventual future contracts and tenders with the government. The desire for standardization and the quick development of high-speed computing capacity devices were, in his eyes, his guidelines for solving computational problems. Also, in parallel to such considerations, von Neumann was expert in wording a description of a well-organized system of high-speed and efficient calculating devices of quality higher than that of ENIAC, while the rest of the ENIAC team expressed themselves better while employing practical and engineering terminology. Von Neumann wanted and needed a device that would integrate technically all possible advanced means, both in its structure and in its general concept. To achieve this aim he needed two things: a) the financial and human resources to establish a 'center'; and b) freedom of action, both technical and theoretical, unlimited by patent and copyright restrictions. That said, von Neumann knew very well how to fight and protect his own rights, both with regard to game theory and Ergodic theory. As the IAS at Princeton showed some opposition to von Neumann's initiative to develop engineering means in the 'Spiritual Garden of Eden of Theoretical Science', he gladly accepted Wiener's proposal (April 21, 1945) to establish the 'center' at MIT, with von Neumann as head of MIT's Faculty of Mathematics. That would be in addition to the construction of the differential analyzers there '*à la* Bush design', for which the NDRC had set up the Radiation Laboratory for the development of radar. Wiener's project took place within the framework of that laboratory [50]. In addition to this flirt with MIT, von Neumann also negotiated with Columbia and Chicago Universities, in search of the ability to initiate a computing development centers. Once MIT's proposal to von Neumann—to establish the 'center', with a position as head of the Faculty of Mathematics to boot—was secure, he urged the IAS to permit him to construct, within the boundaries of the institute, a prototype of his device, the 'All Purpose Automatic High Speed Electronic Computing Machine', to quote his letter to Frank Aydelotte of August 25, 1945 (von Neumann's Papers at the Library of Congress Archive). Despite the IAS members' opposition, von Neumann succeeded in overcoming all possible obstacles and obtained permission to go ahead with his project, acquiring for the project considerable sums of money from the Army, Navy and the Air Force, and later on also from the Atomic Energy Commission. (Lewis Strauss, retired Rear Admiral, also served on the board of trustees of the IAS, and later on as the chairman of the Atomic Energy Commission.)

On February 16, 1946, a day after the public unveiling of ENIAC, von Neumann moved, with Goldstine as his deputy and with Burks, from the University of Pennsylvania to the IAS. It was von Neumann who arranged the jobs for both of them. Von Neumann tried to persuade and tempt Eckert to join him at IAS but failed; they, and the engineers at Moore, refused to follow him to Princeton. This is no surprise: by then the hostility was open. 'The conflict flared up into an acrimonious dispute concerning priorities and patent rights some months later.' [51].

Wiener was disappointed in von Neumarm's behavior. Nevertheless, he gave him all possible help and even saw to it that the appointment as chief engineer of IAS computers went to von Neumarm's assistant, Julian Bigelow (who had worked with Wiener on the various control projects and developed with him the theory of feedback).

Goldstine argues that von Neumann turned to Frank Aydelotte, then the Director of IAS, in November 1945, to intervene in the Princeton computer project [52]. Goldstine mentions von Neumann's request on November 8 to Princeton 'On the program of the high speed computing project'. This program reflected the 'First Draft' report, with radical changes relating in particular to the graphic printed output. And it discloses exciting evidence: in the meeting on the declassification of ENIAC and EDVAC, the Army Ordnance Department expressed readiness to enter into a contract with the IAS for $1 to secure its receiving copies of any report or drawing of the project ('Minutes of meeting on the ENIAC and EDVAC at BRL', December 7, 1945) [53].

Heims (1982), Randell (1973) and Goldstine (1972) report an additional item connected with the IAS computers, von Neumann and Goldstine. It is the study of the analogy between engineering means such as calculating devices and the nervous system. This analogy began in a paper of 1943 by McCulloch and Pitts, 'A Logical Calculus of the Ideas Immanent in Nervous Activity'. Wiener, enthusiastic about this idea, contacted von Neumann (December 4, 1944) and proposed to set up a common interest group. In a letter to Goldstine (December 22, 1944), he suggested establishing a small study group that he named 'the Teleological Society'. Von Neumann agreed to carry organize a meeting. It took place between 6 and 7 January, 1945, without setting a definite agenda. Later, these meetings directly influenced the history of the computer, as well as the use of terminology in computers, that von Neumarm borrowed from names of the nervous system. Wiener saw cybernetics as a synthesis between engineering and biology, with mathematics as the bridge between them. Eckert disliked it all:

> 'It has always been disconcerting to me that von Neumann would listen to us, discuss many of our ideas with us, and rewrite them with the neuron notation that McCulloch and Pitts had used on some neuron studies and then go out and give talks on the work John [Mauchly] and I had done … without giving any credit to the University of Pennsylvania or to the people who had actually thought of the ideas. I can only guess that he felt that since he had translated everything we were doing from engineering terms into neural terms, he hadn't violated the confidentiality of security clearance.' [54].

In 1954 von Neumann was asked to resign from the IAS (although the construction of the first IAS computer had been concluded by the end of 1951), because of the animosity of his colleagues towards his computer projects [53]. After his death (1957), the computer projects at IAS expired, and in 1958 Goldstine retired from IAS and moved to IBM [56].

On June 28, 1946, the first edition of the 'Trinity Paper' was published; the first edition comprised 175 copies. The second edition, issued on September 2, 1946, was much larger. A copy of all publications of the IAS was sent to the American Bureau of Standards (American Patent Office) in order to place it in the public domain [57]. In October 1955 IBM proposed a consultation contract to von Neumann. By then, Mauchly and Eckert had already completed their UNIVAC [58].

Worlds Meet Again (History repeats itself?)

Goldstine, amongst others, gives an account of the selection of a computer for weather forecasting for the US Armed Forces Joint Chiefs of Staff. There was for it an *ad hoc* selecting committee, so that Von Neumarm and Goldstine were of course among its members. The US Air Force was among the financing bodies of the IAS computers, as it needed a computer for weather prediction. On July 1, 1954, the IBM 701 and the ERA 1103 of UNIVAC, constructed by Mauchly and Eckert, were examined. IBM 701 was found the more suitable for the task [59]. Once again, von Neumann was a consultant to IBM, to the Army and to the Government, all at once. At that particular time, UNIVAC ahead of all other computer firms; nevertheless, IBM's 701 was selected for the task. Von Neumann's manner of involvement helped determine the trend.

Summary

Goldstine's excellent and unique relations with von Neumann, so that most of the sources in this Appendix rest on his 1972 book, *The Computer from von Neumann to Pascal*. At the very least, this precludes complains: Goldstine's accounts are not biased against von Neumarm and not hostile to him. Evidently, their bias is in favor of von Neumann; they exaggerate his role in the history of the computer. Also, Goldstine displays an extensive use of documents and familiarity with first-class sources to which he had free access. Hence, we may gather rather a good picture of circumstances and events during the period in question, from mid-1944 until February 16, 1946. In spite of Goldstine's sympathies with von Neumann, a comparative study of what is written in the primary sources as well as of the interviews with other people that wrote on the same events suggest a picture slightly different from the one he conveys. It remains incumbent on historians to fashion a critical comparative analysis of the situation. As a starting point one conspicuous item may serve: von Neumann never referred to the dispute over internal storage, not even indirectly. This was accomplished by others.

The title given to this Appendix, 'The Borrowed Fame', reflects the position I take on this dispute. Von Neumann always fought for his rights persistently and with determination. He fought back against any threat to his contribution and achievements. In any dispute as to his rights and credit—in game theory or Ergodic theory—he fought with determination. In the present case—of the computer, in particular of ideas related to EDVAC—he abstained from polemics. It was Goldstine who ran this dispute. Later on he entered the fray with Arthur Burks as his proxy, and Burks conveniently changed his mind on this issue. I have refrained from using Burks' account in 'From ENIAC to the Stored Program Computer: Two Revolutions in Computers', in Metropolis (1980), pp. 311-344. For, Burks relies there on Goldstine (1972). As to the credit and origination of the idea of internal storage, to repeat, Burks made a revision in the 'First Draft' tending to relate its origin to Eckert and Mauchly and the rest of the ENIAC team members (p. 339).

From the chronology, the sources and the analysis of the information, I present here three possible answers to the question: what caused the borrowed stature of von Neumann?

1) The Wicked Answer

According to this answer von Neumann was preparing the background for the construction of his own computer based on the know-how and concepts gained by the ENIAC project team. He came to this decision sometime in the period between January and May 1945. Thus, the publication of the 'First Draft', supposed to be confidential, was aimed to serve this goal and to remove any obstacle of copyright or royalty obligations to the original inventors of ENIAC and EDVAC. The disclosure of the report could be closely related to von Neumann, and it is reasonable to assume that it was someone from the military establishment involved in other projects as well, or even Goldstine himself, who tied this to von Neumann. It is also possible that it was an intentional leak by some of the ENIAC team members who were closely related to Goldstine, like Burks, Goldstine's first wife, and others. In the second half of 1944 it was already evident that the war was nearing its end, and people started to think seriously about the future and what was to come afterwards. Nancy Stem is also of the opinion that 'Since von Neumarm was traveling extensively to Los Alamos and other locations it was most practical for him to jot down his thoughts, have Goldstine review them and make suggestions, and then continue to revise then. In 1945 Goldstine, apparently on his own, prepared a formal copy of the latest version of these ideas and distributed it to approximately 20 people. Within a matter of months, many others received copies as well.' This version of Stem (April 1985), given on page 101 of the *Annals of the History of Computing*, coincides more or less with what Goldstine wrote (1972, pp. 195-196):

> 'To illustrate how discussions went—even when von Neumann was away at Los Alamos he participated by mail... I am continuing working on the control scheme for the EDVAC and will definitely have a complete write-up when I return.'

On June 25, 1945, copies were distributed to 24 persons closely connected to the project. That correspondence between von Neumarm and Goldstine went on between February 12 and May 1945.

However, in my discussion with Goldstine (October 22, 1986), I presented to him the above answer and argued that history contradicts his claims. For example, the style of writing of the 'First Draft' is not von Neumann's but Goldstine's. At first he denied that he had written that report. Later on he was ready to admit that he had just edited it. When I pressed him further and insisted that he did not 'just' edit the report but that he had written it, he concluded, noncommittally, that I may read it as I wish. He nonetheless admitted that the decision to circulate the report in more copies than security regulations of ENIAC permitted, and that its distribution to various people outside the project was his own idea, and that it was within his authority to do so. I still doubt, however, that a junior officer, as Goldstine was at that time, had the authority to behave as he did.

When I confronted Goldstine with an even stronger claim, that von Neumann had decided already by the end of 1944 (November-December) to build his own computer and that the 'First Draft' report was a part of a wider plot, Goldstine replied bluntly: 'It is correct that we wanted to build our own computer, I had no intention of sitting behind a desk for the rest of my life after the war.' A handwritten letter from von Neumann to Wiener of March 1945says explicitly that Eckert and Mauchly should not be given exclusivity in their development and that it should be put to the benefit of all, in order that others should be able to develop a device of their own. At the beginning of 1945, von Neumann was negotiating with Columbia University and the University of Chicago the possibility of establishing there his own independent development of a computer project.

2) The Naive Answer

The representative of this answer is Goldstine. This answer is that von Neumann was not aware of the issue of patents and legal copyrights.

> 'It has been said by some that von Neumann did not give credit in *his* [my emphasis, A. A.] First Draft to others. The reason for this was that the document was intended by von Neumann as a working paper for use in clarifying and coordinating the thinking of the group and was not intended as a publication… Through no fault of von Neumann's, the draft was never revised into what he would consider as a report for publication. Indeed, not until several years later did he know that it had been widely distributed.'

Here Goldstine takes the blame for the publication of the draft while attributing its composition to von Neumann. Goldstine does not go further to refute the impressions so fortuitously created by the publication of the draft, in violation of the confidentiality of the EDVAC, recognizing von Neumann as the primary or sole source of the idea presented there and, in particular, the ownership of the internal program storage concept.

This answer presents von Neumann and Goldstine as pure academics with no other interests, and no commercial aspirations in particular, unlike Mauchly and Eckert. Nonetheless, they were the only participants in the conference held at the Moore School on April 8, 1947, who brought their own attorney to discuss patent matters.

3) The Balanced Answer

According to this answer von Neumann was a victim of competing interests and conflicts of interest as a double consultant and servant of many masters, unconsciously mixing the conflicting interests between the Manhattan Project and the ENIAC-EDVAC project and more. Thus, the report reflects von Neumann as a scientific consultant who provided up to date, state of the art information in the domains of logic and technology, and the report also represents him as a technical consultant to the BRL and the Army, who expected the Army to order its future devices, a kind of 'technical logical specification' for government tenders. The 'Trinity Paper' should be considered similarly as a document written in particular for a contract with the military. My examination of the original 'Trinity Paper' among von Neumann's papers in the Library of Congress at Washington DC, I verified that it was a part of a contract with the military.

I now add a fourth answer, which I term Eckert's answer.

4) Eckert's Answer

Eckert claims this in *Computer* (1976), Metropolis (1980) and *Datamation* (1962) (see note [54]).

> 'von Neumann would listen to us, discuss many of our ideas with us and rewrite them in the neuron notation ... without giving any credit to the University of Pennsylvania or to the people who had actually thought of the ideas. I can only guess that he felt that since he had translated everything we were doing from engineering terms into neural terms, he hadn't violated the confidentiality of the security clearance.'

This answer is a synthesis of two previous answers: the wicked answer (answer number 1 above), the result of a plot to strip Mauchly and Eckert of their inventions, together with the naive answer (answer number 2 above), that von Neumann was not aware that, despite his wording the ideas that the ENIAC team had developed the McCulloch and Pitts neuron notation, he was violating the security acts and plagiarizing from the inventors and developers of the ideas implemented in ENIAC and EDVAC.

'The road to Hell is paved with good intentions'. Perhaps. The result was still the same. It is evident that the legal rights of the original inventors (I use 'inventors' rather than 'developers' in its legal sense as in the patent laws, not its sense as used in this study), the members of the ENIAC team headed by Eckert and Mauchly were badly infringed. The credit, rights and fame, were taken away from them and transferred solely to von Neumann, without justification. Peculiarly enough, von Neumann never tried or honestly troubled himself to remedy this distortion. This falsification is present today in many a computer science book that attributes the development of the modern computer almost fully to von Neumann. So, in addition to the fame and the prestige that fall so undeservedly on von Neumann by having infringed on the rights of those who had earned it, he gained considerable material remuneration as well.

Many anomalies appear here:

a) The authorship of the 'First Draft' report.
b) The publication and distribution of such a document, in violation of the confidentiality of the security clearance regulations, by a junior officer of the rank of lieutenant or captain.
c) The order for exposing a classified device to the press and public by people who were not among the initiators and thinkers of the idea, including even opponents of the very concept of an electronic device.
d) The twofold involvements and conflicts of interest of von Neumann, in his undertaking as a team member on the ENIAC project and in his desire to construct his own computer somewhere else (note his address to MIT and Columbia and Chicago University) even before the tension rose that led to the falling out between the ENIAC team members. Even earlier, his flirtation with the Army, RCA and Princeton are curious, if not more than that. It is possible that the opposition in Princeton to the construction of a von Neumann computer resulted from another factor, namely, the refusal of the RCA Laboratories there to accept the ENIAC project in April 1943 that raised doubts on the practical feasibility and operation of a device that had some eighteen thousand vacuum tubes. The decision was taken then to construct ENIAC at the Moore School. To repeat, von Neumann received and examined proposals to establish a computer center under the patronage of Columbia and Chicago Universities, that he ultimately rejected [60].
e) The withdrawal of the commitment of the Government, more precisely, of the Legal Branch of the Ordnance Department, to carry out the preparations for the patent application:

> 'In connection with this development provision we have submitted to the Patent Branch a report dated 30 June 1945 by Dr. von Neumann in connection with EDVAC and we also have had submitted certain disclosures in regard to embodiments involved in EDVAC by Dr. Mauchly and Mr. Eckert. Obviously we can't prepare two applications for patent on the same disclosure ... If not, the question is simple because the report in our opinion based on such facts as we now have is a publication. When I say publication I mean that it is a bar to the grant of a valid patent to anyone.'

f) These were the words of Joseph P. Church of the Legal Branch, chairman of the conference held to discuss the patent matters (April 8, 1947). Eckert and Mauchly were frustrated by the declaration that the 'First Draft' was in the public domain, rendering them powerless to contest any patent claim on what it presented. Alas, the University of Pennsylvania had no true interest in the patent. The rescue for Mauchly and Eckert came from an unexpected direction, giving the

Government no choice but to back down. With no patent application, other parties, like Bell, would thus later try to block the free exploitation of the technology by the military at great expense.

g) The proposal of tempting positions to the ENIAC team members by von Neumann to persuade them to move with him to the IAS. He asked even Eckert to join him, but canceled the offer soon, arguing that seeking a patent violates academic freedom.
h) The inception of the IAS computer project on February 16, 1946, one day after the public unveiling of ENIAC (February 15, 1946).
i) An interview published in the *New York Times* (1946) stressed von Neumann's dominating, unique role as the developer of calculating devices was emphasized, without mention of the contributions of others. So, once again, confrontation flared up, this time IAS and RCA challenging Mauchly, Eckert and the Moore School team. However, this time he was forced to retract his statements and apologize (see Stern 1981, pp. 83-84). This may serve as a minor example of the many faces of von Neumann, his refusal to employ Eckert, his greed and his pursuit of prestige and fame.

With the exceptions of Goldstine and Burks and other few von Neumann fans, most people find him not sympathetic, to put it mildly. He has gained a lot of esteem as a scientist: he was quick to grasp ideas, he was hardworking and had an exceptional power of analysis and computation. But his claim that the concept of internal program storage was his exclusive idea is highly objectionable. Even Burks, who edited part of von Neumann's collected works, dissents (Metropolis 1980) with view of the internal storage as exclusively the idea of von Neumann and the claim that only he deserves the credit for it and not Mauchly and Eckert and the rest of the ENIAC team. Burks admitted to me that he revised his view of and his esteem for von Neumann's view on contribution to the development of the computer. Despite the considerable resources that he provided the IAS team, they lagged behind Mauchly and Eckert and others, including the computer developers of the Bureau of Standards, whom Goldstine's book overlooks.

Was it a Coincidence?

In 1947 and 1948, the Electronic Control Company, Eckert and Mauchly's little firm, had two military contracts. Both contracts were on top secret projects. In early 1948 it was disqualified from receiving classified material due to serious security problems, in particular in relation to Mauchly. As a result, the contracts might have been cancelled. The firm fell into debt, and eventually Mauchly and Eckert had to sell out to Remington Rand. Strange things happened there. Let me skip the details (for which see Stan Augarten 1985 *Bit by Bit: An Illustrated History of Computers*, Appendix, pp. 289-294). Early in 1948, the Army's Intelligence Division investigated the firm. Then, on October 6, 1948, the FBI were asked to conduct 'a complaint type of investigation' on Mauchly and other suspects. By November 18, 1948, Mauchly had been cleared of misconduct or disloyalty. However, on January 31, 1950, the Philadelphia District of the US Army informed the firm, now called the Eckert-Mauchly Computer Corporation, 'that the department of the Army had denied security clearance for your firm and particularly … John W. Mauchly ...'. He received back his top secret security clearance on August 8, 1949, and it applied to all Army and Navy contracts. Nevertheless, he had to resign from the presidency of his company, which he did on March 8, 1951. The whole affair ended on December 3, 1952. Mauchly, an innocent victim of anti-Communist hysteria and an 'intellectually honest' individual, was castigated for having signed a petition of the Association of Philadelphia Scientists that urged the President and the House and the Senate Military Affairs Committee to adopt laws that would replace the military control of atomic energy with civilian control. It took only eight years for Mauchly to be restored to his position of trust.

Conclusions

It is exceedingly difficult to determine the motives behind von Neumann's behavior in this case of the 'First Draft' and the internal storage. His continued silence on the authorship of the 'First Draft', is very unpleasant. Stem claims (1985, p. 101) that 'later von Neumann acknowledged that the ideas in the draft were a result of a group effort'. I have found no indication of any such acknowledgement, neither by von Neumann, nor by Goldstine. Very likely, Eckert and Mauchly conceived the idea of the internally stored program in the very early stages of the ENIAC project. In their progress report of December 31, 1943, they refer to this idea obliquely:

> 'No attempt has been made to make provision for setting up a problem automatically. This is for the sake of simplicity and because it is anticipated that ENIAC will be used primarily for problems of a type in which one set-up will be used many times before another problem is placed on the machine.'

When von Neumann joined the project, he anticipated the needs of the calculations he required for the hydrogen bomb. (These were of a scale different from what ENIAC was initially intended to solve.) Possibly, being more aware of calculating needs in general than others on the ENIAC and EDVAC projects, in particular with regard to the speed of calculations, von Neumann also anticipated much faster computers than ENIAC. The irony is that the first problem to be run on ENIAC was part of von Neumann's calculations for Los Alamos during November-December 1945, while the work for the BRL had to wait. Therefore, it is most likely that it was in order to avoid procedural, legal, and other formalities, that von Neumann, assisted by Goldstine and others, took measures such as he was accustomed to, in order to be able to use freely as many computers as were available. This then was all in order to proceed with the work on ENIAC as a consultant while simultaneously breaking ground for his own computer. Goldstine's argument is feeble that all of this was done for the sake of the distribution of know-how for pure academic and scientific benefit; it is facile. Admittedly, Von Neumann was troubled (as were Edward Teller and Theodore von Karman) and occupied with the problem of how to preserve US superiority against the Soviet Union in technology in general and in nuclear and strategic weapons technology in particular. He therefore joined the Rand Corporation as a consultant where game theory was used experimentally for strategic decisions [61]. Von Neumann had no interest in divulging the secrets, in exposing the know-how, of devices that could be used for the development of nuclear weapons or other strategic means, as he knew very well. He also knew the importance of the computer to the American overall strength. Hence, the objection to putting ENIAC in the public domain was not purely academic and not for the benefit of all, as Goldstine claims. On the contrary, it was intended to enable von Neumann to design and construct computers for the needs he considered as vital for the needs of the military and the Atomic Energy Commission. And, indeed, most computers designed after the IAS were constructed for installations linked with the Atomic Energy Commission (GEORGE, JOHNNIAC, MANIAC, ORACLE) and for the military.

It is about time, after so many years, that the fame borrowed without consent should be returned to its right owners, the members of the ENIAC team and, in particular, Mauchly and Eckert, with compound interest for hardship and mental suffering that they endured. Some claim that the publication of the 'First Draft' and the 'Trinity Paper' brought benefit to humanity, since it prevented the payment of huge sums of royalty for the idea. This is a vain argument. It could be argued against any patent rights. Clearly, patent rights were instituted in order to encourage invention. The 'First Draft' and the 'Trinity Paper' still have great influence: they have caused the crystallization of the computer in its two senses: they fixed the patterns of the design and development of new computers and they caused the freezing and paralysis in the development of ideas and concepts of computers. This is what is known today as 'John von Neumann's bottleneck', which researchers struggle to overcome these days.

I shall conclude with a passage from Burks (1976) in Metropolis (1980, pp. 311-312):

> 'There has been a long controversy over "who invented the stored-program computer?" Unfortunately, this question is over simplistic. The development of the stored-program computer took place in many steps and involved many people.. ENIAC was revolutionary: it was the first electronic, digital, general purpose scientific computer... The second revolution was the stored-program computer'.

Burks, saw two main stages in the development:

> 'Pres and John [Eckert and Mauchly; A. A.] invented the circulating mercury delay line store, with enough capacity to store program information as well as data. Von Neumann created the first modern order code and worked out the logical design of an electronic computer to execute it.'

On 'First Draft' Burks says:

> 'In March 1945, von Neumann spent two days at the Moore School having extended conversations with Pres, John, Herman [Goldstine; A. A.] and me about the EDVAC... After these meetings Johnny went off and wrote a draft report on the design of EDVAC. Without his knowledge, this issued as 'First Draft of Report on the EDVAC' (von Neumann, 1945), undoubtedly, he would have given credits to others. In my personal opinion these would have gone primarily to Pres Eckert and John Mauchly, and secondarily to Herman Goldstine and myself.' (p. 339).

I have no dispute with this.

To conclude, in my opinion the publication of the 'First Draft' was a part of a greater and more general plot of von Neumann and his faction: at a certain point in time between the end of 1944 and the beginning of 1945 they resolved to design and develop their own computers and base it on ideas and techniques crystallized in the work of the ENIAC-EDVAC team that they tried to develop further. The mastermind was von Neumann; Goldstine and others. The naivest of these was Wiener.

On September 27, 1944, when it was evident to all that Mauchly and Eckert were working towards claiming a patent for ENIAC, a resistance formed against this move to rob the original inventors. The refusal of Mauchly and

Eckert to recognize the rights of other members of the team for their contributions as co-inventors and their demand for a total and comprehensive patent created tension and resulted in a division within the ENIAC team. Only a person as dominant and authoritative as von Neumann could shatter and undermine the prominent positions of Eckert and Mauchly on the ENIAC project. Therefore, it was Eckert and Mauchly who arose as the standard bearers of the other faction. The impending conclusion of the War, and the fear of what may happen afterwards, drove some of the members of the ENIAC team into the hands of von Neumann, who controlled an abundance of resources. The indecisive stand of the University of Pennsylvania prevented the patent restraining the controversy crisis. It resulted in the inescapable confrontations and schism within the ENIAC team and thus in the University of Pennsylvania's loss of its leading role in the electronic computer domain. Admittedly, at a certain stage negotiations took place between the University of Pennsylvania and von Neumarm, in efforts to achieve some cooperation in the development of electronic calculating devices, in which the theoretical part was to be undertaken at the IAS and the practical at the Moore School. The negotiations failed. Possibly they were a mere part of a smokescreen that von Neumarm used to camouflage his plan to construct his own calculating device on its superior design, to be constructed much more quickly than any other calculating device planned at the time. His plan was never to be.

Notes

1] Paul Armer, 'An introduction', *Datamation* (Sep. 1962), p. 24.

2] Honeywell vs. Sperry Rand, US District Court of Minneapolis Fourth Division.

3] J. Mauchly, 'The use of High Speed Vacuum Tubes Devices for Calculating', reprinted in full in Randell (1973), pp. 329-332.

4] Randell (1973) pp. 289-290.

5] Anon, 'Report on an Electronic Difference Analyzer', Moore School of Electrical Engineering, University of Pennsylvania, Philadelphia, 8th April 1943. The authorship of the document is under dispute, although the authorship of its original First Draft of April 2, 1943, is attributable to Brainerd. See Goldstine (1972), p. 149, endnotes 1 and 2, as well as my reference to it in Chapters 3, 4 and the Summary of Part II of the present study and my article on it, 'An Analysis of the April Moore School Proposals Leading to the ENIAC'.

6] Goldstine (1972), pp. 149-153; Jan Rajchman, 'Talk', *Computer Museum Report*, vol. 13 (Summer 1985), p. 10.

7] Goldstine (1972), pp. 131-133 and 155.

8] Heims (1982), p. 180; Hodges (1983), p. 300; S. Ulam (1976), pp. 141, 154, 155 and 213. Ulam claims that the amount of multiplying calculating operations of ENIAC is equivalent to what the schoolchildren of the entire world could perform in fifty years (p. 213), and that this is one of the primary causes of the development and construction of electronic computer (p. 155). This claim is evidently groundless, though it is possible that after the capabilities of ENIAC for such types of calculations were perceived, development of the electronic computer greatly accelerated. There was a dispute within the NDRC about the choice between electronic and electro-magnetic technologies in the development of computers. This was settled by 1949.

9] Hodges (1983), p. 300; it is also found among von Neumann's papers in the Library of Congress.

10] *Ibid.*

11] On the Hanover meeting see T. R. Hollocroft, 'The Summer Meeting in Hanover', *American Mathematical Society Bulletin*, vol. 46 (Nov. 1940), pp. 859-861. Despite the absence of Mauchly's name from the list of attendees, it is evident that he participated in the demonstration of the 'Complex Computer' of Bell-Stibitz, and he even acquired a sample of its punched paper tape.

12] Hodges (1983), pp. 300-301; von Neumann's Papers Collection, Library of Congress.

13] Goldstine (1972), pp. 182-183 and 185-186.

14] *Ibid.*, pp. 185-186.

15] *Ibid.*, p. 185.

16] *Ibid.*, p. 186.

17] *Ibid.*, pp. 186-187.

18] *Ibid.*, p. 187.

19] *Ibid.*

20] *Ibid.* p. 191; H. D. Huskey, 'On the History of Computing', *Science*, vol. 180 (11 May 1973), p. 589.

21] Goldstine (1972), p. 196.

22] *Ibid.*

23] Huskey (1973), p. 589.

24] *Ibid.*

25] *Ibid.*; N. Metropolis, and J. Worlton, 'A Trilogy on Errors in the History of Computing', First USA-Japan Computer Conference Proceedings Tokyo 1972. On the concept of the internal stored program and on its initial influence the authors deem one of the three errors in the history of computing. The two others were the extent to which the developers of the early computers, what I call automatic program-controlled digital calculating machines, were aware of Babbage's work, and the early history of MANIAC (the Los Alamos computer that went into operation by early 1952; Metropolis was among its developers and builders).

26] Goldstine (1972), p. 215.

27] *Ibid.*, p. 216.

28] *Ibid.*

29] Brainerd, Eckert, Goldstine and Mauchly, 'Description of the ENIAC and Comments on the Electronic Digital Computing Machines', *Applied Mathematics Panel Report 171, 2R*, Moore School of Electrical Engineering, University of Pennsylvania, Distributed by AMP, NDRC, 30 November 1945

30] *Ibid.*

31] *Ibid.*, p. 217.

32] *Ibid.*, p. 220.

33] *Ibid.*, p. 227.

34] *Ibid.*, pp. 227-232.

35] *Ibid.*, p. 220-221.

36] *Ibid.*, p. 223.

37] *Ibid.*, pp. 223-224.

38] *Ibid.*, page 224; taken from 'Informal Report in re Disclosure of John von Neumann's First Draft of a Report on the EDVAC'; written shortly after April 1946.

As to the issue of storage memory, the options were as follows: those based on electrostatic storage tubes, and those based on ultrasonic delay lines, also named electrostatic tube storage. In it, the phosphorescent coating of a metal lattice is energized by means of an electron-beam in a cathode-ray tube in a computer monitor or television set. It is possible to charge each defined spot of the screen with electrostatic energy by means of the very tiny electron beam that scans the screen a few hundred times per second. The storage is binary. The energized-charged spots represent the digit '1' and the other spots represent the digit '0'. To keep the information imprinted this way it is re-energized or 're-refreshed' rapidly.

This type of tube memory was reached in parallel in the USA by Zworykin and Rajchman and in the UK by F. C. Williams at Manchester University. (This is the Williams-tube memory.) Williams had applied this method during the war in a radar system to distinguish automatically friend from enemy aircraft. Atanasoff had preceded the idea of rechargeable-refreshing electrostatic memory while utilizing electric condensers as components of storage memory in his device. The advantage of the electrostatic tube storage as against punched paper tape and the like is in its enabling random and parallel access to the information stored there. It was considerably cheaper and it occupied much less volume then acoustic storage.

Acoustic storage could be constructed in several different ways. The type relevant here is called the mercury ultrasonic delay line. In a glass pipe tube of the length of about 1.5 meter, a piezoelectric crystal was attached to both ends of the tube filled with mercury. When an electrical pulse was impressed on the crystal at the initial end of such a tube, the crystal vibrated and thereby sent a sonic wave down the mercury. Upon arrival at the other end, the sonic disturbance compressed the terminal crystal that then emitted an electrical disturbance, mirroring the input signal but delayed by a fraction of time due to and according to the length of the column of delaying material in the tube. This interval or delay between the entering pulse (input) and the outgoing pulse (output) can be stored. This technique was utilized in the EDSAC (1949) by Wilkes at Cambridge and was twenty times faster than that of magnetic tape storage. One major advantage of the mercury delay line was how storage was fixed until it was disconnected from the mains. Another advantage was how the mercury delay line did not require recharging, as the electrostatic tube did. However, it was cumbersome and, as storage technology it was only applied for a very short period (1949-1954). Mauchly and Eckert were the first to consider the possibility of using this technology in the EDVAC before von Neumann joined the project. Eckert wrote a report on the mercury delay line on June 28, 1943; it included seven handwritten pages; it is Exhibit 1570 of the Honeywell vs. Sperry Rand Trial.

39] Goldstine (1972), pp. 224-255 as well as: 'Minutes of Conference held at Moore School of Electrical Engineering, 8 April 1947, to Discuss Patent Matters', reprinted in full with Nancy Stern's Introduction in *Annals of the History of Computing* (April 1985), pp. 99-116.

40] Goldstine (1972), p. 221. On the patent policy at universities see, for example, S. Ulam (1976), p. 124. The University of Wisconsin enjoyed royalties from a patent connected with milk treatment invented by one of its professors, used for better salaries that attracted more sought-after faculty. On the patent policy of the University of Pennsylvania, see the Honeywell vs. Sperry Rand document in the Charles Babbage Institute, Exhibit 1350, Box 5.

41] S. Heims, *John von Neumann and Norbert Wiener: From Mathematics to Technology of Death*, MIT Press (1982).

42] Heims (1982), p. 239. Lewis Strauss (1896-1974), a former banker who assisted President Wilson in many ways during World War I, was Rear Admiral in the Navy and the right hand man of James Forrestal, the then Secretary of Defense. Strauss had great interest in technology and science and was an enthusiast thereof. In the summer of 1945, he discussed the possibility of constructing a general purpose computer for weather forecasting with von Neumann. Like Mauchly, von Neumann was also deeply and consistently interested in the issue of long term weather forecasting, though for other reasons (p. 187).

Strauss was a member of the board of trustees of Princeton and the IAS. When the occasion arose to extend Oppenheimer's term of directorship at the IAS, von Neumann wrote that he had 'serious misgivings' and recommended in his stead psychologist Detlow W. Bronk (who was elected later on). It was he who brought along von Neumann as a member of the Atomic Energy Commission and who later nominated him in 1955 as its Chairman.

43] See Heims (1982) p. 237; as well as S. Ulam (1976). Ulam compares von Neumann and Wiener in dealing with the military: 'Norbert was difficult in his dealings with the military, whereas Johnny always got along with them.' And on von Neumann's ingratiating fondness of generals and authority, Ulam writes:

> 'Johnny seemed to admire generals and admirals and got along well with them. Even before he become an official himself he spent an increasing amount of time in consultation with the military establishment, and I believe [this] was due more generally to his admiration for people who had power… I think he had a hidden admiration for people of organization that could be tough and ruthless.' (pp. 23-232).

44] Heims (1982), p. 237.

45] Heims (1982, p. 198)

> "Von Neumann always sought for career and position which would bring him power and influence within the administration. It seems that during the war that was exactly was his career plan for peace time. His technical expertness in the development of weapon systems could leverage such a career. Indeed, the government has adopted innovation as a pillar of armament policy."

46] According to J. Bronowski, von Neumann was increasingly involved in projects with private firms, industry and administration. These enterprises brought him closer to power. Based on Heims (1982), page 473, footnote 58.

47] Heims (1982), p. 61.

48] Burks, Goldstine and von Neumann, 'Preliminary Discussion of the Logical Design on an Electrical Computer', Princeton (28 June 1946).

49] Zuse (1984) *'Der Computer mein Lebenswerk'*; Turing (1936).

50] At MIT, Wiener and Julian Bigelow developed a fire control system according to a statistical mathematical principle for optimal future prediction from inadequate information that rests on the Ergodic principle. The Radiation Laboratory, established at MIT in the beginning of World War II, studied mainly problems linked to fire control and radar.

51] Heims (1982), p. 469.

52] Goldstine (1972), p. 241.

53] *Ibid.*, p. 242.

54] J. P. Eckert, 'Thoughts on the History of Computing', *Computer* (Dec. 1976), p. 65.

55] Heims (1982), p. 276.

56] Goldstine (1972), p. 319.

57] *Ibid.*, p. 256.

58] *Ibid.*, p. 330.

59] *Ibid.*, pp. 329-330, von Neumann as the Chairman of the Committee.

60] Goldstine (1972), p. 241. In November 1945 von Neumann went to Chicago to tell Robert M. Hutchins, then the President of the University of Chicago who was making a great effort to revitalize that university, that he was rejecting Hutchins' proposal of setting up a computer center project there.

Some of the documents in von Neumann's collection at the Library of Congress Manuscript Department in the Madison Building, Washington DC are indicative of his extensive public relations. On March 12, 1945, Julian Huxley, Chairman of UNESCO, wrote to von Neumann asking him for information about electronic calculating machines:

> 'Dr. J. Simpson of Chicago suggests that I should write to you for information as to the present stage of development of the new electronic calculating machine which you have in your institute ... I shall be grateful for any information you can give.' (von Neumann collection, Box 3, Folder 2).

(Von Neumann's reply to this letter of March 12, 1945, bears the date March 28, 1946. Von Neumann made several mistakes in dating. Still, it appears that this one is Huxley's, as at that time he was working on preparations for the UNESCO conference, due to be held in November 1946, in which Aiken participated as a lecturer on calculating devices.)

The reason this request was addressed to von Neumann, as suggested by a Chicago resident is provided at the beginning of the above reference. In his reply of March 28, 1946, von Neumann makes it clear that it is a digital device and not a 'continuous variable or analog machine' (*Ibid.*).

In a letter of May 1, 1945, von Neumann committed himself to a consulting contract, signed with IBM, to assist the Watson Laboratory at Columbia University, concerning advanced mathematical know-how to calculating machines and to electrical or mechanical instruments for statistical needs. He committed himself to providing one tenth of his time to IBM and to transfer to that firm any improvement or invention that he would discover then. Paragraph 4 of the contract excepted ENIAC from this, whereas any invention made while consulting ENIAC or NDRC was also be given to IBM, subject to the condition of his contracts with the government (page 3 of the contract).

On November 20, 1945, von Neumann and Wiener were informed that Princeton, RCA and IAS: 'Have decided to undertake a joint high speed automatic electronic computer development.' (*Ibid.*)

A handwritten letter by Wiener of March 24, 1945, proposed von Neumann for a position at MIT. On August 14, 1945, von Neumann proposed to George Harrison (1898-1979) that he accept the position of head of the Department of Mathematics at MIT.

On 1st February 1945 von Neumann wrote to Wiener that it would be desirable to add Eckert and Chandrasekhar of Moore (professor at the Yerkes Observatory) and possibly also Stibitz to the project (Box 28, File "Theory of Automata", von Neumann MIT Archive).

These documents support my opinion that the ENIAC patent issue had nothing to do with the crisis in the ENIAC team and should not be linked to it. Von Neumann and his faction were discretely making all possible arrangements to transfer the activity of the development of electronic calculating devices from the University of Pennsylvania to the Princeton IAS. To cite Goldstine (1972, pp. 239-241):

> '...it was clear to me by the summer of 1945 that the development of computers had to continue and in a more normal peace time mode. I therefore had a number of conversations with friends to gain some feeling for what was possible and desirable... Whatever the reasons, the leadership of the Moore School was almost at an end... After many long conversations between von Neumann and me on the subject of who would carry on computer development, the idea gradually became clear to both of us that if we were to continue, "we" would have to be the ones to do it.'

Thus, the publication of the 'First Draft' and other material concerning ENIAC were a part of a larger plan that evolved sometime between November-December 1944.

61] The Rand project, known later as the Rand Corporation of Santa Monica CA, was established in 1946 by the US Air Force in order to work 'on the broad subject of international warfare'. Later on, it became a world center for the cultivation and advancement of game theory. Von Neumann was a consultant there from 1947 on.

That the initial version of game theory displays an inbuilt bellicose bias is becoming increasingly widely recognized these days.

APPENDIX C

INDEX OF *DRAMATIS PERSONAE*

The ENIAC team consisted of the following persons: Grist Brainerd, Arthur Burks, Joseph Chedaker, Chuan Chu, James Cummings, John Davis, Harry Gail, Adele Goldstine, Harry Huskey, James Hyman, Edward Knobeloch, Robert Michael, Frank Mural, Thomas Sharpless, and Robert Shaw, in addition to Herman Goldstine, Mauchly and Eckert.

Aiken, Howard Hathaway (1900-1973). For details refer to Chapter 3.

Alt, Leopold Frantz (1910-2011). Austrian-born American mathematician, a member of the National Bureau of Standards and author of articles and books on the history of the computer. One of the mathematicians at the BRL, Aberdeen and in charge of a device constructed by Bell which was set up there.

Andrews, E. G. A telephone engineer and one of the pioneers at Bell on calculating devices.

Atanasoff, John Vincent (1903-1955). See Chapter 3.

Babbage, Charles (1791-1871). English philosopher and mathematician, developer of a pilot model of a difference engine of two levels of differences and designer of several other difference and analytical engines.

Babbage, Henry Provost. Son of Charles, constructed a part of the 'Mill' processor of the analytical engine after his father's design.

Richard Babbage, great-grandson of Charles, an assistant editor of Canada's national farm magazine, *Family Herald and Weekly Star*.

Baldwin, Stefan Frank (1838-1925). American engineer, designer and developer of key-driven calculating devices in 1911. Invented a wheel with protruding pegs in 1875.

Barbour, Edmund D. A Bostonian who designed a paper printed output in a cash register for the first time in 1870 and obtained in 1872 the first patent for a direct multiplying component of the mechanization of Napier's bones.

Baudot, Jean-Maurice-Emile (1845-1903). Engineer and officer in the French Telegraph Corps. In 1874 he got a patent for character code, a punched paper of fixed size binary code. In 1894 he developed the parallel multiplex communication system in the telegraph.

Beauclair Wilfried de (1912-). Born in Switzerland. A mechanical engineer, he joined IPM in Darmstadt in 1936 and was Alwin Walther's assistant there. After the war he worked on Siemens' first electronic projects.

Berry, Clifford (1918-1963). Atanasoff's assistant in the construction of the ABC computer at Iowa State College, 1938-1942. See Chapter 3.

Bigelow, Julian Himley. Norbert Wiener's assistant at MIT; the first chief engineer of the IAS computer project.

Billings, John Shaw (1839-1913). US Army General Surgeon who was lent to the Census Bureau Office for the 1870 census. He was in charge of the preparation of the 1880 census. They say he advised Hollerith to use Jacquard's punched cards to process the census statistical data.

Bollée, Léon (1870-1913). Designer of mechanical calculating machines and inventor (1889) of a direct multiplication method that mimics the multiplying table by means of a matrix of pegs arranged according to a Pythagorean table. He exhibited this machine at the Paris 1870 exhibition. He could not solve the problem of direct dividing. Only three models of his device were constructed. He was also active in the design of motor cars.

Boole, George (1815-1864). Inventor of Boolean algebra or Binary Logic.

Brainerd, John Grist (1905-1988). Professor, director and Dean at the Moore School. He headed and took formal responsibility for the design and construction of ENIAC. He took no further part in later computer project. He published two pamphlets on the design of electrical circuits: in October 1932, 'Note on the Network Theory', and in January 1933, 'Equivalent Circuits of an Active Network'. He initiated new electrical engineering courses and was co-author of two pioneering textbooks, *High Frequency Alternating Currents* (1931), and *Ultra-High Frequency Techniques* (1942).

Broadhurst, S. W. An electro-mechanical engineer and expert in automatic telephone switching, who worked at the Royal Post Office Research Station located in the London suburb of Dollis Hill. Assisted Flowers in the design and construction of the Colossus.

Bryce, James Wares (1880-1949). One of America's most prolific inventors. He developed many patents related to calculating devices, including electronic circuits. He was one of the three engineers of the Harvard Mark I team at the IBM laboratories at Endicott. Mark I contained several of his major inventions such as high-speed multiplying, dividing and cross-adding systems, as well as the readout and the emitter. As far back as 1915, he envisaged the potentialities of the vacuum tube for calculating and studied its potential use in computation. In 1932 he instituted a research project to develop methods of utilizing the vacuum tube to perform arithmetical operations. He joined IBM as a Chief Scientific Director, after inventing many mechanical devices. He was closely involved in the design and development of calculating equipment for Columbia University Statistical Bureau. He was also involved in the design of the SSEC at IBM (Selective Sequence Electronic Calculator (1945-1949).

Bouchon, Basile. A French weaver in the silk center in Lyon. In 1725 he invented a way to control a silk draw-loom with punched paper tape for designing an automatic weaving of fabric patterns. This partially automated the tedious setup process of the draw loom in which an operator lifted the warp threads using cords. In 1726 his co-worker Jean-Baptiste Falcon improved on his design by using punched paper cards attached to one another, which made it easier to change programs quickly. The resultant machine was semi-automatic: it required a manual feed of the program.

Burks, Walter Arthur (1915-2008). Philosopher, mathematician and computer scientist, one of the original members of the ENIAC team. He claims to be a co-inventor of ENIAC. After the split in the ENIAC team, in February 1946, for a short time he joined von Neumann and Goldstine in the IAS computer project.

Burks, Rowe Alice (1920-2017). One of the original members of the ENIAC team and Arthur Burks' wife.

Burroughs, W. S. (1855-1898). American inventor, designer and developer of the first recorded adding machine and pioneer of its manufacture. He developed his first calculating machine in 1885 for commercial applications in certified public accounting (being financed by an accountant). It proved commercially impractical. In 1892 he patented a practical model that had commercial success. In 1886 he founded the American Arithmometer Company, succeeded by the Burroughs Adding Machine Company, established in Michigan in 1905.

Bush, Vannevar (1890-1974). One of America's most prolific inventors in the domain of analog devices. Educator and engineer at the RCA. Headed the USA's scientific war effort, including the Manhattan Project. Developer of an advanced integrating element which enabled the breakthrough in the construction of mechanical and electrical differential analyzers. In 1936, at the American Mathematical Society's Annual Meeting, he set up a program for a new concept in the design of automatic digital calculating devices. Initiated in 1937 the first investigation for the feasibility of applying electronics for a digital program-controlled calculating device, the Rapid Arithmetical Machine Project at MIT.

Byron, Augusta Ada, Countess of Lovelace (1815-1852). The only legitimate daughter of poet Lord Byron. Her heavily annotated lengthy notes to her translation of the paper by Luigi Federico Menabrea, '*Notions sur la Machine Analytique de M. Charles Babbage*' (1842) provide one of the best possible descriptions and interpretations of the basic ideas and principles of Charles Babbage's Analytical Engine.

Cajori, Florian (1859-1930). Educator and mathematician, whose works on the history of mathematics were among the most eminent of his time.

Caldwell, Samuel H. (1904-1960). Member of MIT who supervised and participated in the development of the Rapid Arithmetical Machine at MIT during the period 1939-1942.

Dodgson, Charles Lutwidge (1832-1898). Better known by his pen name, Lewis Carroll, the celebrated author of *Alice's Adventures in Wonderland, Through the Looking-Glass, and What Alice Found There*. He was a mathematical logician, photographer and novelist. He tried to contribute application of logic for practical needs by means of logic machines.

Chambers, Carl Covalt (1910-1987). Professor and second dean of the Moore School. He was involved in the training courses of human computers for the BRL and the differential analyzer in the period 1940-1943. In summer 1946, from July 8 to August31, he directed a special course entitled 'Theory and Techniques for the Design of Electronic Computers'.

Chandler, W. W. Recruited by the Post Office in 1936. Gained expertise in electronic valves for trunk line switching. Assisted Wym-Williams with the development of the high speed fourth rotor during the Enigma crisis in 1942. He was also one of the designers and developers of the British Colossus.

Chase, George C. Chief engineer at the Monroe firm. Encouraged Aiken to carry on with the development of his device, first within the framework of Monroe and later on at IBM.

Chedaker, Joseph. Engineer in charge of the construction work of ENIAC.

Church, Alonzo (1903-1973). An Argentinean-American logician who moved to the IAS, Princeton. Together with Turing, he gave in 1936 the precise meaning of the term and concept of computability.

Coombs, Allen W. M. (1911- 1995). One of the Colossus designers.

Comrie, Leslie John (1893-1950). New Zealander mathematician and astronomer who moved to the UK. Became superintendent of HM Nautical Almanac of the Royal Naval College, 1930-1936. Later on he founded Scientific Computer Service. Superb calculator, knowing all there was then to know on the use of the Brunsviga, the Hollerith and the NCR machines for astronomical calculations. By 1928 he applied the Hollerith tabulator to form tables of the moon's positions. One of the first to apply commercial calculating equipment for scientific calculations. It was Karl Pearson who introduced Comrie to the use of the Brunsviga (11th November 1918).

Conant, James Bryant (1893-1978). President of Harvard and the Chairman of the NDRC during the period of constructing ENIAC (1943-1946).

Couffignal, Louis (1902-1966). Frenchman who was one of the first to advocate the use of binary notation and technology for calculating devices (1933). Designer and developer of calculating devices before World War II. Headed the project of the French computer after the War at the Pascal Institute in Paris. Already by 1933, he had distinguished between calculators (in today's terminology) and computers. Classified the calculating devices according to their error likelihoods and the necessary involvement of the human operator in their function.

Crawford, Perry O., Jr. (1917-2006). Investigated the design of a matrix calculator based on Bush's ideas in 1939 in his BSc thesis., and went on to design an electronic digital calculator for anti-aircraft fire control systems in which an automatic program-controlled calculating device plots, scans and adds, subtracts, multiplies and divides two numbers fed by a punched paper tape, then sorts, prints or punches it. He also persuaded MIT to switch to the development of digital calculating devices in in preference for analog, resulting finally in the Whirlwind computer.

Dirks G. & G. Father and son developers of a magnetic drum and electronic accounting machines during World War II (1943).

Dreyer, Hans Joachim (-1980). Trained as an electrical engineer. IPM staff member. Participated in 1944 in the development of a digital program-controlled computing device at IPM on IBM equipment.

D'Ocagne, Philbert Maurice (1862-1938). One of the developers of the discipline of Nomography, the collection of curves which enable an easy graphical solution for complex equations; coined the term. The development of nomograms helped civil projects carried out in France, particularly during the rapid expansion of the railroad. D'Ocagne made one of the first classifications of calculating devices according to the function of its components. Author and co-author of many books on calculating devices; considered in France before World War II expert in the field.

Durfee, B. M. Engineer of the IBM team who worked with Aiken on the development of Mark I and was recognized by him as co-inventor.

Eccles, W. H. (1875-1966). Co-author of the historic description of the one-stroke relay that operated by triggering electrical impulses. It is used in vacuum-tubes flip-flop switches. See also Jordan.

Eckert, John Presper, Jr. (1919-1995). The chief engineer on the ENIAC project. See Chapter 3.

Eckert, Wallace John (1902-1971). Astronomer; a graduate of Yale University. One of the founders (1933) of Columbia University's Astronomical Calculating Laboratory, known as the IBM Watson Laboratory. One of the first in the USA to apply commercial calculating equipment for scientific calculations. During the 1940s he was involved in the design and development of several calculating devices for IBM, including the SSEC.

Falcon, Jean-Baptiste (?-1765). A Lyon silk-weaving artisan; introduced the punched paper tape control in the silk draw-loom.

Faraday, Michael (1791-1867). Discovered the electric motor and dynamo.

Fibonacci, Leonardo (c.1170-1240?). Known as Leonardo of Pisa. Considered the lead mathematician of the Middle Ages. Studied in North Africa. In his *Liber Abaci* (1202) he helped to introduce the Arabic decimal notation to Europe.

Flowers, Thomas H. (1905-1889). Senior member of the Colossus team. Joined the Post Office Research Station at Dollis Hill in 1930 as an engineer. His major research interest was long distance signaling, in particular transmitting control signals, thus enabling replacing human operators with automatic switching equipment. In 1931 he started research on electronic valves for telephone switching. The work resulted in an experimental toll dialing circuit.

Forrester, Jay Wright (1918-2016). Developer of the Tube and Magnetic core storage memories at MIT. Together with Everett he headed the Whirlwind Project at MIT, a real-time computer for aviation control. In 1944 he worked on the Aircraft Stability and Control Analyzer at the Servomechanism Laboratory that he founded with Gordon Brown at MIT in 1940. Crawford's influence, which subsequently brought about the Whirlwind Project, helped shift from analog to digital techniques.

Fry, Thornton, C. (1892-1991). Head of the mathematical department of Bell Laboratories in New York. He designed and constructed an analog mechanical calculating device, the isograph, designed to find roots of complex polynomials. Prompted the design of a calculator based on Stibitz's binary adder, capable of multiplying and dividing complex numbers, thus paving the way for the important series of telephone relay calculating devices at Bell Telephone Laboratories.

Gaspar Schott (1608-1666). Jesuit mathematician who published a volume with an account of mechanical computing methods and with a description of mechanical devices such as the *Organum Mathematicum*. See Chapter 1.

Goldstine, Heine Herman (1913-2004). In April 1943, he encouraged and promoted the submission of an official proposal by the Moore School for the construction of an electronic calculating device. Became the liaison officer of the Army to the ENIAC project. Von Neumann's assistant in the IAS computer project after 17th February 1946.

Goldstine, Adele Katz (1920-1964). First wife of H. Goldstine. Worked on the ENIAC project and wrote the complete technical description for it. Through her work in programming ENIAC, she was also instrumental in converting it from one that needed to be reprogrammed each time to one able to perform a set of 50 stored instructions. After the War, she continued her programming work with von Neumann at Los Alamos.

Grant, George Barnard (1849-1917). American calculating device inventor who constructed several models of a difference engine (the first in 1870).

Grillet de Roven, René. A French clockmaker, employed in the Louis XIV court. In an article of 1678 he mentions the machines of Pascal and Petit (a device based on Napier's cylindrical rods) and claims that he had integrated the Pascal wheels with Petit's cylinders and obtained a 'Magic Machine carrying out all the arithmetical operations.'

Hamann, Christal (1870-1948). A well-known, successful German designer. Designed the Mercedes Euklid calculator and invented the proportional lever that the Rheinmental Marchant and Monroe calculating machines employed. A 1932 pamphlet of his describes various electro-magnetic calculating devices, mainly various forms of multipliers, but also a device for solving sets of linear equations with a paper tape for data input.

Hamilton, Francis E. (1898-1972). One of the IBM participants in the design and construction of Mark I. Recognized by Aiken as co-inventor of Mark I. Chief engineer of the IBM SSEC project.

Hahn, Philipp Matthäus (1739-1790). A German priest and inventor. In about 1763 he devised a heliochronometer—precision sundial—that incorporated the correction for the equation of time. In 1773 he designed one of the earliest mechanical calculators, of which two have survived to this day. A renowned clockmaker, several horological museums display his works, including the *Deutsches Uhrenmuseum* that has a mechanical orrery—model of the solar system—and a *Weltmaschine*—world-automata.

Hartree, Douglas Rayner (1897-1958). British physicist, mathematician, computer pioneer, designer and constructor of analog devices at Manchester University. He was involved in various calculating projects during World War II. In the mid-1930s he built a mechanical device for solving differential equations, based on the differential analyzer of Vannevar Bush. During World War II he was involved with the ENIAC project in the US. At the University of Cambridge, he introduced an approximation scheme that served as the basis for most atomic calculations and for quantum wave mechanics. The method—sometimes called the Hartree-Fock method after Vladimir Fock (1898–1974), who generalized Hartree's scheme—is used to describe electrons in atoms, molecules, and solids.

Heaviside, Oliver (1850-1925). Mathematician and physicist, who worked in 1870 as a telegraph operator. After 1874 he studied the theoretical aspects of telegraphic communication, electricity transformation and, later on, the refraction of radio waves from the ionosphere.

Hazen, Harold L. Director of the Electrical Engineering Department at MIT (1938-1952). He was involved in the development of analog and digital devices at MIT and at the NDRC.

Henry, Joseph (1797-1878). American developer of the electric motor and the electro-magnetic relay (1828). Built an electro-magnetic telegraph (1830).

Huskey, Harry Douglas (1915-2017). One of the first of the ENIAC team. Joined University of Pennsylvania in 1943 to teach in the Math Department. Worked at the Moore School for extra money. Under Arthur Burks, Huskey was to report on how the ENIAC worked. In 1946, Huskey left the Moore School for the National Physical Laboratories (NPL) in the UK to work on the Automatic Computing Engine (ACE) project. Huskey briefly commented on Turing and his contributions to the project and his personal accomplishments. He joined the National Bureau of Standards (NBS) in 1947 and helped build the Standards Eastern Automatic Computer (SEAC). In December 1948, he left the NBS for the Institute of Numerical Analysis (INA) at UCLA to build the Standards Western Automatic Computer (SWAC), and a project on an electronic magnetic drum-type machine. While at INA, Huskey took a year's leave to help Wayne State University set up their computer center (1952-1953). He designed there the Bendix G-15 drum-computer.

Hollerith, Herman (1860-1929). Utilized the punch card and the electro-magnet for counting, sorting and statistical data processing.

Hoelzer, Helmut (1912-1996). German electrical engineer and remote-controlled guidance specialist. He built a fully electronic analog device in 1941 in Peenemunde, while working on Wernher von Braun's Nazi long-range rocket development team. The device was used for simulations and trajectory calculations at Peenemunde and later at Fort Bliss, Texas.

Jacobson, Jewne. A Jewish clockmaker from Nieswiez in Lithuania, who in 1770 developed a mechanical calculating machine.

Jacquard, Joseph Marie (1752-1834). He was recognized in 1805 as the inventor and developer of the automatic punch card controlled draw-loom. His device rested on the earlier work of Falcon, Bouchon and others.

Jevons, William Stanley (1835-1882). British political economist who constructed one of the first logic machines capable of solving complex logical problems faster than humans.

Jordan, Frank Wilfred (1882-1941). Developed with Eccles (see above) a trigger relay circuit device in 1919, constructed from low pressure gas-filled tubes (three-electrode thermionic vacuum tubes) to latch a single piece of information by creating binary states of set and re-set, as in the flip-flop, in the circuit. Their paper (1919) was the first publication on electronic technology storage and the creation of two distinct stable states with such technology.

Kelvin, Lord, see Thomson, William (1824-1907).

Kircher, Athanasius (1602-1680). A German Jesuit. Tried to make an imprint of cylindrical Napier rods. Teacher of Gaspard Schott at Wurzburg University. One of the giant volumes that he wrote dealt with calculating techniques. See Chapters 1 and 2.

Lake, Clair D. (1888-1958). IBM engineer, one of the developers of Mark I. In the early 1920s, at IBM, he developed the first Total Printing and Listing Tabulator. Lake also developed the Type 512 and 513 high-speed reproducers and many machine-related technological functions, such as summary punching. Lake met Harvard's Howard Aiken in early 1938 and became chief engineer for the Automatic Sequence Controlled Calculator (Mark I) project in May 1939. Aiken considered Lake, Hamilton, and Durfee as co-inventors of Mark I.

Lehmer, Derrick Henry (1905–1991). A table compiler who, with his wife Emma, pioneered the use of computers in number theory and probing number theoretical problems. In 1933, he built an extremely fast photo-electric number-sieve for solving problems in number theory.

Lehmer, Derrick Norman (1867-1938). Father of Henry (see above). Applied mathematician who in 1929 improved the card stencils method for easily finding so-called quadratic residues, which have a fundamental role in number theory. He developed a variety of mechanical and electro-mechanical factoring and computational devices, such as the Lehmer sieve, built together with his son.

Leibniz, Baron Gottfried Wilhelm (1646-1716). See Chapters 1 and 2.

Ludgate, Percy E. (1883-1922). A Dublin accountant who in 1903 started to design an analytical machine. There is no evidence that he ever tried to construct the machine. He tried later to design a simpler machine more in the nature of a difference engine, which probably never got past the design stage.

Marquand, Allan (1853-1924). Philosopher at Princeton University. He designed several devices, but only one was built for him—by Charles R. Rockwood, Jr., professor of mathematics there—a logic machine for solving syllogisms. He prepared a schematic of the electrical circuits and relays.

Mauchly, John William (1907-1980). Initiator of the ENIAC idea. See Chapters 3 and 4.

Mauchly, Kathleen McNulty Antonelli (1921-2006). Mauchly's second wife. She was one of the six original programmers of the ENIAC.

Mauchly, Mary (?-1946). Mauchly's first wife. One of the women computers at the Moore School.

Maxwell, James Clerk (1831-1879). The famous physicist who published the first theoretical work on feed-back control mechanisms like governors.

McClelland, George William (1880-1955). President of the University of Pennsylvania during the construction of ENIAC and during the crisis on it.

Menabrea, Luigi F. (1809-1896). Italian general and politician. Editor and publisher (1842) of Babbage's lecture in Turin of 1840. See also Lovelace.

Metropolis, Nicholas Constantine (1915-1999). Physicist, who together with Stanley P. Frankel ran the first problem on the ENIAC for Los Alamos and von Neumann during November-December 1945. He and Frankel arrived in summer 1945 to learn about ENIAC (probably before August 28, 1945). Developer of MANIAC.

Michelson, Albert Abraham (1852-1931). The famous American scientist who constructed, with Samuel W. Stratton (1861-1931), a harmonic analyzer, a twenty-element machine based upon Kelvin's 1876 analyzer.

Molina, Edward C. D. (1877-1964). An American engineer, known for his contributions to telegraphic engineering. In 1901 he entered the AT&T research department, later Bell Labs. His 1906 invention of relay translators translated the pulses of dialed decimal pulses into relays.

Monroe, J. R. (1883-1937). An American calculating machine manufacturer who developed in 1920 a calculating device with a division mechanism based on a single action of the operator. In 1911 he developed a calculating device activated by push buttons.

Morland, Samuel (1625-1695). English scientist who adopted the idea of iterative adding for the multiplicative operation in the calculating machine. Challenged by Leibniz, he constructed (1773) a calculating device that operated on the principle of Napier's rods.

Müller, Johann Helfrich (1746-1830). A German military engineer who in 1783 had the idea of constructing a calculating device based on the difference principle and of a printing mechanism. See Chapter 1.

Napier (Neper), John (1550-1617). Theologian and mathematician involved in the development of arms. He is considered as the inventor of the logarithm and its applications to calculations. His work on logarithms is in his 1614 publication, *'Mirifici Logarithmarum Canonis Descriptive'* (description of the miracles of the logarithmic canon). Also famous for the development of the Napier Rods (named after him), a calculating aid for multiplying, for raising of powers and for extracting square roots.

Newman, Maxwell Hermann Alexander (1897-1984). British Mathematician and codebreaker at Cambridge. Turing's tutor in 1934-1936. Since 1942 he worked at Bletchley Park; of the designers of the Colossus and the Manchester University computer.

Odhner, Willgodt T. (1845-1905). A Russian/Swedish engineer who in 1890 developed the idea of the pin wheel and cam disc, the principle on which the calculating machine Brunsviga works.

Overhoff, Gerhard. Zuse's partner in the firm established in 1943 in Berlin.

Pascal, Blaise (1623-1662). See Chapter 1.

Peirce, Charles Santiago Sanders (1839-1914). American philosopher and mathematician who worked as a physicist for the US Coast Guard. In a letter to Marquand, he proposed to apply relays for logic and demonstrated how to obtain the binary gates of 'and' and 'or'. He knew of Babbage's work.

Pearson, Karl (1857-1936). Popularizer of statistics. During World War I his Biometrics Laboratory at the University College of London served, computing shipping statistics, tables of stresses for airplane propellers, and trajectories for anti-aircraft guns. His 1919 *Tracts for Computers*, that uses 'computers' to denote people who compute.

Pender, Harold (1879-1959). First dean of the Moore School for Electrical Engineering, University of Pennsylvania (1923-1949). During his tenure ENIAC was constructed there.

Phillips, William (?-1968). British mathematician and proponent, designer and developer of binary calculating devices based on telephone relays, photoelectric cells and electronic valves. Urged to apply the binary notation for general use in 1935. He started to work on the design of the ACE in 1943, at least two years before Turing's arrival at the NPL.

Pottin, H. Frenchman who in 1874 first used in cash registers, the printed paper earlier developed the American inventor Barbour (see above).

Powers, James Legrand (1871-1927). A mechanical engineer, born in Odessa, the Ukraine. Graduated from the Technical School of Odessa. Migrated to the United States in 1889. He had some experience in developing office machines that won him several patents when the US Census Bureau hired him 1907. He developed a system rival to Hollerith's based on mechanical punch equipment. His equipment was used in the 1910 census. In 1911 he founded the Accounting and Tabulating Machines Company that underwent several takeovers and mergers to become Remington Rand in 1927. in 1955 it merged with Sperry Gyroscope. Since then it is known as Sperry Rand. In 1952 the Mauchly-Eckert firm was taken over by Sperry as a separate division, known as Sperry UNIVAC.

Rajchman, Jan Alexander (1911-1989). A member of RCA Laboratories at Princeton NJ. Designed and developed electronic storage and counting means out of radar and fire-control systems. By 1939 he was already using digital electronics for directing the laying of anti-aircraft guns. See also Zworykin.

Richardson, Lewis Fry (1881-1953). Englishman, pioneer of long-term weather prediction based on finite-difference numerical-process techniques.

Schaeffler, Otto (1838-1929). Austro/German, improved a model of a telegraph printer and the independent inventor and developer of the 1874 signaling and printing telegraph that used a binary code (like that of Baudot) of five symbols operating on five keys on a keyboard, enabling the representation of the 26 letters of the alphabet (a teleprinter). He met Hollerith in Vienna and started marketing and developing tabulating equipment. He obtained an Austrian patent for the integration of an electrical connecting plug board, May 30, 1895, like that in a manual telephone exchange, but with tabulating equipment. it could link 77 counters and 240 sorters.

Scheutz, Pehr George (1785-1873). A Swedish printer. Influenced and encouraged by Babbage, he constructed the first model of the differential machine (1843) and two additional models. See Chapter 1.

Scheutz, Raphael Edward (1821-1881). Son of George, an engineer who participated in the construction of his father's second difference engine.

Schickard, Wilhelm (1592-1635). Considered today the designer of the first known mechanical calculating device in 1623. See Chapter 1.

Schott, Gaspar (1608-1666). See Gaspar above.

Schreyer, Helmut (1912-1984). Zuse's collaborator and an independent designer and developer of electronic calculating devices in Germany (1936-1945). See Chapter 3.

Shannon, Claude Elwood (1916-2001). Founder of the switching and information theory at MIT and Bell laboratories and of information theory.

Sharpless, Thomas Kite (1913-1967). Engineer. One of the original members of the ENIAC team.

Shaw, F. Robert. One of the original ENIAC team.

Shockley, William Bradford (1910-1989). Born in England. Researcher at Bell Laboratories from 1936. Developed the transistor with W. H. Brattain. One of the first to think of supersonic storage memory. Won the Nobel Prize in Physics for 1956. During World War II he worked in the US Navy, where he developed anti-submarine warfare technology. There he also worked on acoustic storage based on delay lines.

Stanhope, Charles James (1753-1816). Developer of logic machines and calculating means in the Leibnizian tradition.

Steinmetz, Charles Proteus (1865-1923). German physicist who immigrated to the USA. One of the most distinguished electrical engineers of this century. Worked in the computing department of General Electric, where he developed a method to apply the complex numbers for more efficient calculations of power network supply lines, which was later on also adapted to telephone communication lines. He was also responsible for the deeper introduction of mathematics into electrical engineering in general and the training of electrical engineers in mathematics in particular.

Stem, Abraham (1769-1842). A Jewish-Polish scholar who developed a series of calculating devices that performed the four basic arithmetic operations, powers and square roots of up to six numerical units (1817).

Stibitz, Robert George (1904-1995). Mathematician. Worked at Bell Laboratories and developed an electro-magnetic binary calculating device (1937). One of the designers of the Bell computer series. See Chapter 3.

Steiger, Otto (1858-1923). A Swiss engineer who lived in Munich and designed a calculating machine, Millionaire, in which a direct multiplying element was integrated (1892).

Strowger, Almon B. (1839-1902). Undertaker from Mansfield, USA, who worked in his youth as a Morse telegraph operator in a railway company. He developed a relay bearing his name to use in the automatic telephone exchange (1891).

Sturgeon, William (1783-1850). Developed an electro-magnet which had several layers of wire with insulator (1825). This resulted in a considerable extension of the power of the electro-magnet.

Thomson, Sir William (Lord Kelvin) (1824-1907). Developer of analog devices such as the harmonic analyzer and its integrating element.

Tauschek, Gustav (1899-1945). Austrian engineer and inventor, holding 169 patents, many of them sold to IBM. Developed calculating devices for accounting and tabulating equipment. developed a photo-electric digital reader (1932). He also designed a magnetic disc.

Torres y Quevedo, Leonardo (1852-1936). Suggested an electro-magnetic solution for Babbage's ideas (1893). Designer and builder of automata and calculating devices in binary notation and technologies with relays.

Travis, A. Irvin (1904-1980). One of the Moore staff. In 1938 he proposed the consideration of the feasibility of integrating multiple desk calculating machines in order to obtain a large scale digital calculating device. Supported the construction of electronic electrical machines. Later vice president of the Burroughs Computer Company.

Turing, Alan Mathison (1912-1954). Mathematical logician. Described in his 1936 paper the structure and principles of the universal machine for computable problems. At Bletchley Park (1938-1945) he was among the designers of the Bombs and the Colossus. Participated in the design of ACE, of NPL, and of the Manchester University computer. Conceived the computer as an intelligent device capable of mimicking human behavior. In design he favored minimal use of hardware. See Chapters 3 and 4.

Ulam, Stanisław Marcin (1909-1984). Mathematician. Developed with von Neumann the Monte Carlo method.

Valtat, R. L. A Frenchman who obtained a 1935 patent for a calculating device based on binary notation and technology. Among the first proponents then to apply binary notation for calculating devices.

Vaucanson, Jacques (1709-1782). A famous French automata constructor, who in 1750 developed an automatic silk draw-loom based on work done by his predecessors (Bouchon and Falcon) in Lyon, using the punch card method. He designed a model of a fully automatic loom controlled by a pegged cylinder.

Verea García, Ramon Silvestre (1833-1899). A Spanish writer, newspaper publisher (in New York) and engineer. Inventor of a calculator with an internal multiplication table. In 1878 he obtained a patent for multiplication by mechanizing the Napier rods. He also patented a direct-multiplying machine that was the second patented machine of this type (after the machine of Edmund Barbour).

Von Neumann, John Louis (1903-1957). Mathematician. Joined the ENIAC team sometime between August 7 and September 9, 1944. His involvement in the ENIAC project is controversial. His contribution to computer development is extensive after 1945, bringing great acceleration to the design and construction of computers in the USA and elsewhere. Viewed the computer as a particularly fast calculating means. In his design, he emphasized the hardware. See Appendix B, 'The Borrowed Fame'.

Walther, Alwin (1898-1967). German mathematician who in 1928 founded the IPM Institute for Applied-Practical Mathematics in Darmstadt. There, emphasis was given to the utilization of mathematics and calculating devices by engineers (see also Steinmetz), a trend established by the German mathematician Felix Klein (1849-1925) in Göttingen. Several famous analog and digital mechanical, electrical and electronic devices were developed at IPM (Darmstadt slide rule).

Warren, S. Reid (1908-1996). Headed the EDVAC project at the Moore School, University of Pennsylvania.

Weaver, Warren (1894-1978). Chairman of the Mathematical Panel of Applied Mathematics of the NDRC.

Weiner, Bernard (1891-1942). Studied at the Polytechnics of Prague and Vienna. After World War I, filed a patent application (November 8, 1923) for an *'Electrische Rechnen und Schreibmaschine'* (electronic calculating and typewriter machine) that was approved (March 2, 1928). His device had keys for entering data and instructions. The instructions were imprinted in the hardware and activated by keys. The device was designed with binary technology of relays and electro-magnets utilizing decimal notation. The prototype has not survived. The patent stimulated much interest among calculating device manufacturers, including NCR. The metal mills of Vitkovice established a special department in which Weiner developed his ideas to design a totally automatic device. The German occupation cut short this initiative. Weiner perished in a concentration camp in 1942.

Wheatstone, Charles (1802-1875). English physicist and inventor. Developed an electric telegraph.

Wiberg, Martin (1826-1905). Swedish developer of the difference machine according to Scheutz's design (1862).

Wiener, Norbert (1894-1964). Mathematician. Proposed the development of electric, photo-electric and electronic calculating devices based on binary notation in early 1940. Tried without success to found a center for computer production at MIT with von Neumann.

Wilkes, Maurice Vincent (1913-2010). Applied mathematician. Worked on the development of radar. Participated in a course organized at Moore for electronic calculating devices in 1946. From 1946 he headed the Cambridge University Mathematical Laboratory and developed there EDVAC, the first electronic device after von Neumann's 'First Draft'.

Williams, Frederic Calland (1911-1977). British developer of a storage tube bearing his name. In 1940 he constructed an automatic curve-follower for the differential analyzer.

Williams, Samuel Byron. Relay-system design engineer at Bell Lab.

Womersley, John R. (1907-1958). Worked with Douglas R. Hartree (1897-1958) on the application of the differential analyzer to partial differential equations (1937). Director of the NPL department of mathematics, where Turing designed the ACE, he apparently tried to construct a model of Turing's universal machine with electro-magnetic relays (1937-1938); the project was canceled as impractical due to the slowness of the device. The first non-American visitor to the ENIAC project (March 12, 1945).

Wood, Benjamin Dekalbe (1894-1986). He founded the Columbia Statistical Bureau in 1928 with IBM's aid. He had the first university laboratory for educational statistics to support his educational reform by conducting large scale educational testing.

Wynn-Williams, C. E. (1903-1973). British physicist who in 1932 developed elementary particle counters in the Cavendish Laboratory in Cambridge. In 1942 he was called to Bletchley Park. He worked there on an electronic photo-electric device called the Robinson.

Xavier, Thomas Charles de Colmar (1785-1870). An Alsatian, French mathematician who devised and built in 1820 his first arithmometer while serving in the French army. This was a calculating machine that performed addition, subtraction, multiplication, and division. It was the first mechanical calculator to achieve commercial success. It was use up to World War i see Chapter 1.

Zuse, Konrad (1910-1995). A German and *the* computer pioneer. See Chapters 3 and 4.

Zworykin, Vladimir Kosma (1889-1982). Served in the Czar's army signals corps. Migrated to the USA in 1919. From 1920 he worked at Westinghouse in Pittsburgh. In 1923 he applied for a patent for the iconoscope, which is the forefather of the television's tube-cathode ray tube, an important component in the television camera and the electronic microscope. In 1928 he obtained a patent for color television. From 1929 he worked at the RCA laboratories, NJ. He also developed night vision facilities before World War II. During the War he worked at the RCA laboratory at Princeton where he developed with J. A. Rajchman and others electronic counting circuit components for fire-control systems.

INDEX OF NAMES