

History of Computing

Raúl Rojas

# Konrad Zuse's Early Computers

The Quest for the Computer in Germany



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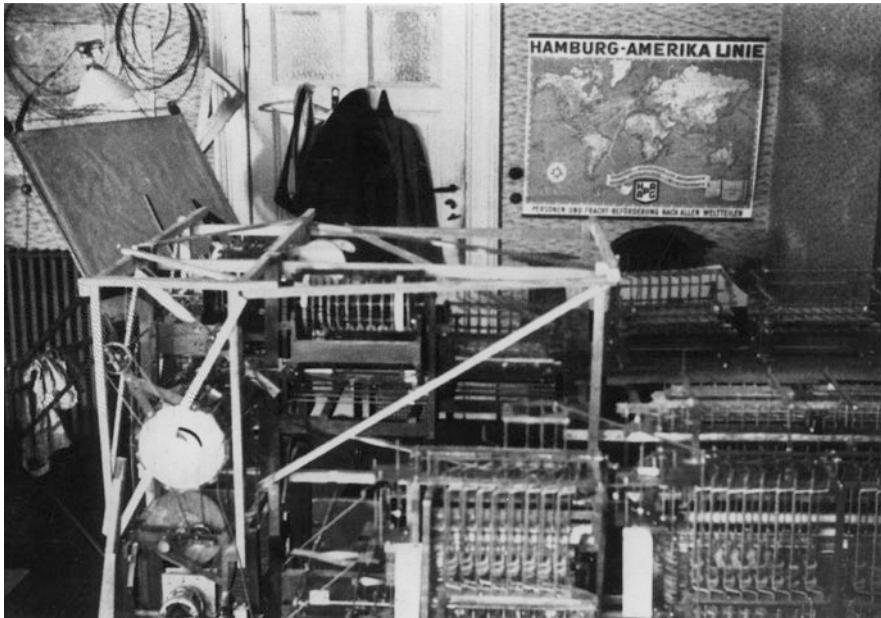
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Raúl Rojas

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Nevada, USA

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*Quando orientur controversiae, non magis  
disputatione opus erit inter duos  
philosophus, quam inter duos computistas.  
Sufficiet enim calamos in manus sumere  
sedereque ad abacos, et sibi mutuo (accito si  
placet amico) dicere: calculemus.<sup>1</sup>*

*Gottfried Wilhelm Leibniz*

---

<sup>1</sup> “If controversies were to arise, there would be no more need of disputation between two philosophers than between two calculators. For it would suffice for them to take their pencils in their hands and to sit down at the abacus, and say to each other (and if they so wish also to a friend called to help): Let us calculate.”

# Foreword

This book describes the historical development of the architectures of the first computers built by the German inventor Konrad Zuse in the period 1936–1945. Although these machines are prominent in Germany, this is not the case in other countries. In many books on the history of the computer, Zuse’s work receives only passing mention. However, as the various chapters in this volume show, the kind of computer architecture that Zuse developed is closer to modern computers than the architectures of the Harvard Mark I or the ENIAC, the two American machines most often celebrated as the world’s first computers.

Over the years, I have published most of the material in this book as articles in academic journals, Internet sites, and conference proceedings. I started writing about Zuse’s machines in 1994, so putting this book together meant reorganizing all the contributions in a coherent way. Some articles published in German have been translated for this volume. Each chapter contains references to the original publications. The advantage for the reader is that this collection brings together all stages of an amazing intellectual puzzle, the invention of the computer, no less, into a single volume.

For this book, I have chosen to keep each chapter as a stand-alone piece, so that they can be read in any order. Sufficient redundancy has been provided with explanations at the beginning of each chapter to ensure clarity of context. The reader can think of this book as a collection of essays that, after thirty years of research, are now closely interwoven.

To make the book easier to read, the preface has been written as a kind of “executive summary” containing the most important general information and chronology. It is intended for the super-busy reader. Then, for those who are just busy, the first chapter gives a comprehensive overview of the computers Zuse built from 1936 to 1945, that is, the Z1, Z2, Z3, and Z4, as well as other more specialized machines. Subsequent chapters deal with the architecture of each computer, culminating in the description of Plankalkül, the first proposal for a high-level programming language.

It is my sincere hope that the curious reader will venture out and peruse the entire book. Some chapters are easier to understand than others. For example, the

Z1 computer, the mechanical calculator, is more difficult to digest than the relay machines, the Z3 or Z4. After the overview in Chap. 1, the reader can skip to the chapters on the Z3 or Z4 if she or he prefers, and then return to the chapter on the Z1. Chapter 2 is easy to follow: it describes the historical circumstances for the development of electronic computers in the USA and Europe.

This book is for the curious and the adventurous. Students and practitioners of computer science should have no trouble following the material in all chapters. Readers from other disciplines can certainly get the main message, perhaps by adopting the nonlinear reading strategy mentioned above. Start with the concise summary that follows, and you will be well on your way to retracing the steps of a remarkable intellectual adventure.

Reno, USA  
August 2023

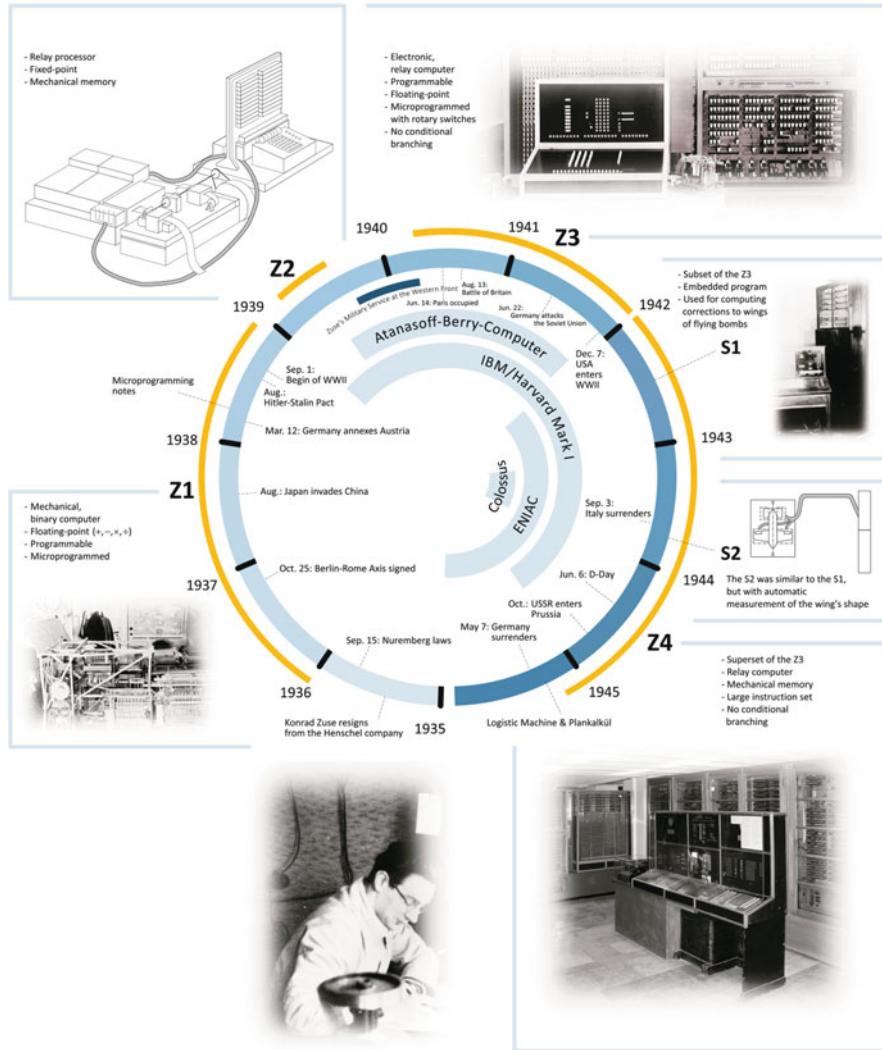
Raúl Rojas

# Preface

Konrad Ernst Otto Zuse was born in Berlin in 1910 as the son of Emil and Maria Zuse. He is generally considered the father of the computer in Germany. He started thinking about automating computations as a student in the mid-1930s and built a mechanical computer from 1936 to 1938/1939. The machine was called V1 (*Versuchsmode*ll 1, i.e. Experimental Model 1). By the end of the war, he had built three more important computers: the V2, V3, and V4. The four were renamed Z1, Z2, Z3, and Z4 to avoid any association with Wernher von Braun's V2 rockets. While the Z1 was a purely mechanical device (based on what Zuse called "mechanical relays"), the processor logic of the Z2, Z3, and Z4 was based on electromagnetic relays. Nevertheless, the mechanical memory of the Z2 and Z4 still used sliding metal components as two-state memory elements. The logic design of all four machines was completely binary: the decimal input was converted to base two for all internal calculations in the processor. The result was converted back to decimal for display (except in the Z2, which displayed the result as 16 bits).

The Zuse machines Z1, Z3, and Z4 used the floating-point representation, where numbers are stored as a binary mantissa with its sign and an exponent of base two (for example,  $+1.010 \times 2^3$ ). The Z2 transitional machine was a fixed-point prototype, a proof of concept. All four computers had a processor, a memory, an input keyboard, and a visual display for results. Programs were punched, instruction by instruction, on 35 mm film tape. The processor of the Z1 could perform the four basic arithmetic operations, the Z2 only a subset. The Z3 could also extract square roots of numbers. The Z4 had a much larger instruction set than any of the other machines.

Zuse was drafted twice during the war. On both occasions, he was able to get his discharge from the front so that he could work on structural analysis for the Henschel Flugzeug-Werke, while at the same time continuing to build his calculating machines through his own company. He built two small special machines for the military (called S1, in 1942, and S2, in 1943/1944), which executed a hardwired program that calculated the appropriate profile corrections for the wings of flying bombs (Zuse was in charge of these computations at the Henschel factory in Berlin). Both machines were binary and used fixed-point numbers.



Chronology of Zuse's computers and important events during World War II

In 1941, after successfully demonstrating the Z3 relay machine computing determinants, Zuse's company received first a loan and then a military contract to supply Henschel with the Z4, a machine that would be faster, have a larger instruction set, and several punched tape readers, one for the main program and the others for program libraries. The Z4 was nearing completion by the end of the war but remained in storage for several years after the surrender. Finally, it was refurbished and leased to the ETH Zurich in 1949–1950. This concludes the early history of Zuse's computers. With this successful transaction, Zuse was able to

restart his company, the first computer start-up in Germany. The figure above shows the chronology of Zuse's early computers and how it corresponds to important events during the war. The diagram also shows the overlapping development of three important American computers and Colossus, a British war effort.

The ten years of Zuse's *Sturm und Drang* period (1935–1945) end with two theoretical results: the design of the so-called logistic machine and its profound relationship to the programming language “Plankalkül”, the first high-level computer language ever proposed.



Photograph of Konrad Zuse working on the computer Z4 (Image: Konrad Zuse Internet Archive, <http://zuse.zib.de/>)

In this book, we follow the development of Zuse's ideas, computer by computer, explaining their architectures and capabilities. As we will see, the main weakness of all the machines was the omission of the conditional jump in the instruction set. Even the Z4, the improved and more sophisticated computer, did not have a conditional jump until the ETH required its inclusion as a prerequisite for acquiring the machine. Until then, Zuse's computers could only perform long sequences of forward calculations, or a single loop obtained by attaching the beginning and end of a punched tape. The conditional jump instruction greatly expanded the Z4's

usefulness for complex numerical calculations. Zuse stated in later years that he was aware of the need for a conditional jump, and even indirect addressing, but that both required the program to be stored in memory in order to be effective (Zuse, 1972). However, given the small size of the mechanical and electromagnetic storage units in his computers, storing the program in memory was out of the question.

Zuse's competition in the USA was represented by three machines at this time: the Atanasoff-Berry computer, a special-purpose binary device for solving systems of linear equations, the IBM/Harvard-Mark I, a massive relay machine unveiled in 1944, and the ENIAC, the first programmable vacuum tube computer, completed in 1945 (Bruderer, 2020). As you can see from the chronology in the figure, Zuse was the early pacesetter for these developments. The Z1 was completed before the American computers were even designed. However, all three American computers could be shown to work before the Z4 was completed. Zuse's initial advantage dissipated during the war.

The Z4 was the computer that Zuse had dreamed of in 1935. Its realization took ten years of intensive work under difficult wartime conditions. The design of Plankalkül crowns these ten years, the most creative of Zuse's life. Plankalkül was a remarkable achievement because it aimed to establish a comprehensive symbolic calculus for computer programs. Consequently, Zuse devised a notation capable of expressing both predicate calculus formulas and equivalent imperative programs. In this sense, Plankalkül is both a logical specification language and an algorithmic language. Using Plankalkül notation, Zuse created the first symbolic processing programs.

It would be another five years after the war before Zuse was able to lease/sell the Z4 to the ETH, but by then the inventor who had designed all of his computers single-handedly had become an entrepreneur, and new machines were increasingly developed by committee in collaboration with his team of engineers. Zuse's company, which was re-established in 1949, operated independently until 1964, when it was acquired by Brown, Boveri & Co. Siemens bought 70% of the company in 1967 and the rest two years later. When it was liquidated in 1969, Zuse KG had delivered 251 computers in Germany and other European countries during its twenty years of operation.

Paradoxically, as late as 1950, when all new computer prototypes in other countries were electronic, Zuse was still thinking about mechanical binary components as low-cost substitutes for relays or expensive electronic tubes. He was certainly the last great maestro of mechanical computers, in the tradition of Babbage's Analytical Engine, but also one of the first builders of electromagnetic computers in the world. His pioneering achievements lie between two intellectual and technological eras, in the transition from the second to the third industrial revolution.

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Raúl Rojas

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Zuse, K. 1972. *Der Plankalkül*, vol. 63 . Sankt Augustin: Berichte der Gesellschaft für Mathematik und Datenverarbeitung.

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My student Alexander Thurm wrote the first Java simulation of the Z3 almost 30 years ago. My colleagues Georg Heyne and Frank Darius were the hearts and minds behind the reconstruction of the Z3 with modern relays. Our first Zuse-related project was to build a modern relay version of the addition/subtraction unit of the Z3. Thorsten Vetter, Wolfram Däumel, Lothar Schönbein, and Peter Zielske developed different parts of the electronics for both projects. Cüneyt Göktekin wrote the user interface for the Z3 reconstruction. He and Gerald Friedland as well as Lars Knipping developed important parts of the Plankalkül interpreter. Mike Krüger, Olaf Langmack, and Denis Kuniß developed the parser and executable code generator for the interpreter. Ludmila Scharf translated Zuse's chess code into Java for an Internet simulation. Hadwig Dorsch provided me with important documents and blueprints of the reconstructed Z1 built for the German Museum of Technology in Berlin. She and Eva Kudrass also gave us direct access to the machine, a rare privilege in a museum.

I must also thank Horst Zuse, Konrad Zuse's eldest son, who over the years has provided insight and support for all of our Zuse projects at Freie Universität Berlin. He was able to raise the entire funding for our reconstruction of Z3. The Konrad Zuse Society was always interested in my research and organized talks on some of the papers that are now chapters of the book.

For many years, the Konrad Zuse Center in Berlin has generously provided the server for hosting all documents in the Zuse Internet Archive, initiated by me and funded by the German Research Foundation (DFG), as well as the simulations of Z1 and Z3. Unfortunately, the development of Java made our applets obsolete. I

would also like to acknowledge the fruitful collaboration with Dr. Wilhelm Füßl of Deutsches Museum in Munich during the successful digitization of Zuse's *Nachlass*. Special thanks to Susanne Schöttker-Söhl for her transcription work on the documents and her contributions to the digitization process.

I would like to thank friends and colleagues who provided valuable feedback and suggestions during the development of this book: Victor Perez Abreu, Rafael Gamboa, Alexander Förster, Michael Engel, David Hemmendinger, Stefan Höltgen, and Eva Kudrass for their suggestions and corrections. I am especially indebted to Prof. Wolfgang Bibel for his assistance in debugging the manuscript and for helping me to clarify the historical achievements contained in Plankalkül. His guidance and expertise were instrumental in ensuring the accuracy and clarity of the content. I would also like to thank Günter Feuer for his meticulous reading of the various chapters. His careful attention to detail and astute suggestions for deletions and consolidations greatly improved the overall readability of the manuscript. I am also grateful to Sarah Hiller for her work in cleaning up the LaTeX code and organizing the references in the book. Philomena Maher read the manuscript and corrected my English. My thanks to all of them.

I would like to express my deepest gratitude to my wife, Magui, and my daughter, Tania, for their unwavering support and understanding throughout my projects. They patiently stood by me during the long hours of work, especially during the intense periods when I was immersed in deciphering Zuse's intricate circuits. It was a challenging journey, but the ultimate satisfaction came from being able to visualize in my mind's eye the harmonious orchestration of interlocking mechanical parts within the first computer in Germany. This book is dedicated to both of them as a token of my love and gratitude.

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# Chapter 1

## Konrad Zuse and the Dawn of the Computer Age



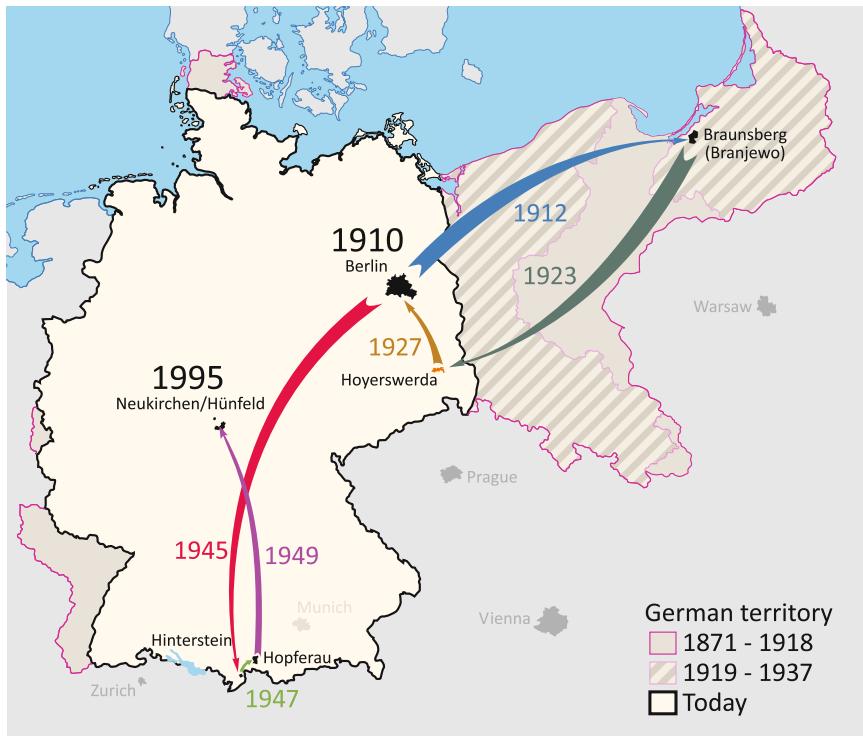
*This chapter provides an overview of the basic facts about Konrad Zuse and his early computing machines, i.e., those built in the period 1936–1945. The chapter summarizes the whole book.*

The inventor Konrad Zuse (1910–1995) is a legendary figure in Germany, where he is widely celebrated as the “father of the computer.” In 1941, Zuse unveiled the world’s first programmable computing machine in his Berlin workshop. The Z3, as the machine became known, was shown to a select group of visitors to demonstrate its capabilities. Young Konrad had begun designing computers long before the war. Against all odds, he persevered during and after the global conflict.

In other countries, however, Konrad Zuse is not so well known. This is not surprising, since most of his early computers were not recognized, either in Germany or abroad, until after 1945. Many American books on the history of computing mention the German inventor only briefly (Campbell-Kelly et al. 2013). Typically, his work receives only a passing mention, even though, as this book shows, modern computers bear more resemblance to Zuse’s Z1 or Z3 than to the American ENIAC or the Harvard Mark I, two other machines built during World War II.

### 1.1 Birth and Education

Konrad Ernst Otto Zuse was born on June 22, 1910 (2 years before the birth of Alan Turing) in Wilmersdorf, now a district of Berlin, as the son of Emil and Maria Zuse. His father was a Prussian civil servant in the postal service. Emil Zuse moved the family to Braunsberg (now Braniewo in Poland) when Konrad was 2 years old (see Fig. 1.1). Konrad attended elementary school in Braunsberg and received his basic education at the local Hosianum Gymnasium (where the famous German mathematician Karl Weierstraß had once taught). In 1923, the family moved again,



**Fig. 1.1** The map of Germany after 1918 showing the location of the cities where Konrad Zuse lived and the year of migration. The shaded parts are the territories lost by Germany after World War II. The birth date is 1910, and the date of death is 1995

this time to Hoyerswerda (a town near the present-day border with Poland). Zuse was enrolled at the local *Realgymnasium*, an institution that prepared students for admission to several technical universities in Germany. In his autobiography, Zuse describes the new environment, which included a local mining industry, as better suited to his technical aspirations (Zuse 1970). It also helped that the school required fewer hours of Latin, a language Zuse detested.

In 1927, Konrad Zuse received his high school diploma (*Abitur*) and soon after began his studies at the *Technische Hochschule zu Berlin* (renamed *Technische Universität Berlin* after World War II). Zuse mentions in his memoirs that he was 2 years younger than the other students (Zuse 1970). Later in life, he regretted that he had not tried to learn more at school.

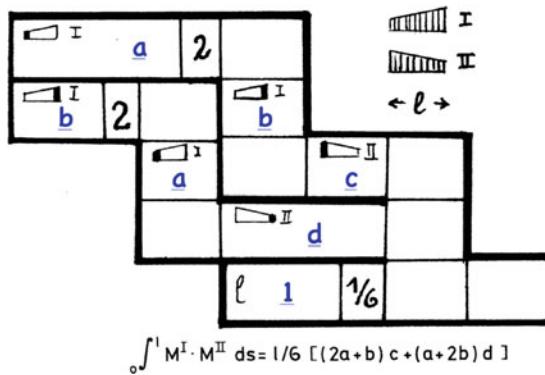
When he enrolled at the university, Zuse had not yet made up his mind about his future profession. He first tried mechanical engineering, then switched to architecture, took a year off, tried graphic design for advertising, and finally, chose civil engineering. Zuse wrote that he eventually discovered that this type of profession was ideal for him because it allowed him to combine his artistic interests

with his technical skills, especially in mechanical design. It was also a profession that gave the student more creative freedom (Zuse 1972). As a high school student, Zuse was already a technical dreamer and tinkerer, often retreating to work with his “Stabil” mechanical set (a kind of German Meccano), which allowed him to build prototypes of complex machines. As a student, he won several prizes for his Stabil constructions (the last in 1928), which he liked to show off to his friends (Rojas 2001).

## 1.2 First Ideas: The Spreadsheet Computer

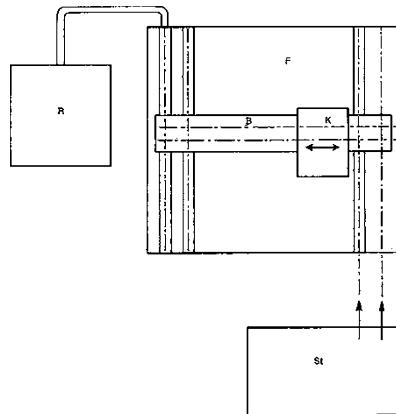
While studying civil engineering at the TH Berlin, Zuse learned to perform highly repetitive structural calculations, such as those needed to determine the stress on structures like bridges or cranes. These calculations were typically performed manually or with the aid of desk calculators. Spreadsheets with all the necessary formulas preprinted on them were painstakingly filled out, row by row, column by column. It was a tedious and repetitive task that led Zuse to consider the possibility of automating this work. In these spreadsheets, the engineer simply had to enter data and follow a fixed computational path. Therefore, he thought, a machine could take over (Kurrer 2010).

In his autobiography, Zuse traces his interest in computing machines back to 1934/35. In 1934, he submitted a “Studienarbeit” on the systematic arrangement of computations for structural analysis (Fig. 1.2) (Kurrer 2010). By then, he was thinking full-time about automating computational tasks. His initial concept was to map spreadsheets onto a plane of memory cells. In each cell, it would be possible



**Fig. 1.2** Example of a spreadsheet for a static forces calculation (Zuse 1970). Numbers in cells are multiplied horizontally and added vertically, until the lowest right cell has been filled. The initial constants (in this case  $a, b, c, d$ ) are written in the cells containing a symbol. That initial data trigger the subsequent computations. The final result, corresponding to the formula at the bottom, is written in the lowest cell to the right

**Fig. 1.3** A read/write head able to displace across a plane for reading and writing numbers from the spreadsheet cells (using vertical pins) (Zuse 1970). The box St manages the control, the box R represents the calculating portion of the device



to store a number using vertical pins representing zeros or ones according to their height. A mechanical device would traverse the entire plane (using something like the mechanism of a modern  $xy$  plotter) and would be able to read numbers from each cell (encoded using vertical pins) for the computations needed in the spreadsheet (Fig. 1.3). It could then store the result in a new cell. The device would be something like a pocket calculator, but with a mobile read/write head going from cell to cell in the planar spreadsheet (Zuse 1970).

The “spreadsheet computer” envisioned by Zuse already contained some interesting ideas. One was to use the binary system to represent positive numbers, the other to represent negative numbers using the complement representation, so that subtraction could be treated as addition with a complementary number. Zuse quickly realized that the memory cells did not have to be arranged in any particular order, as they were in the spreadsheets. If the cells were numbered (i.e., addressable), they could be retrieved by their address. So he went on to design a computer with a processor and addressable memory based on binary numbers and their complement (the two’s complement representation). Also during these years, he developed what he called the “semi-logarithmic” (i.e., floating-point) representation that he would use in all of his early computers. He also wrote a complete description of the binary system and the algorithms he intended to use (Zuse 1937).

We show in this book that Konrad Zuse pursued almost the same basic computer architecture during the period 1936–1945, through different incarnations of the basic ideas. His successive machines were called V1, V2, V3, and V4, with the capital V standing for *Versuchsmodell* (experimental model). The V was changed to Z after the war to avoid any association with the V2 rockets. Between the Z3 and Z4, Zuse built two specialized machines for the German military, the S1 and S2. The S stands for “*Sondermaschine*” (special machine). The S1 and S2 were based on a small subset of the Z3 architecture, but worked with fixed-point numbers (integers).

### 1.3 The Z1 and Z3 Machines

In July 1935, right after graduation, Zuse began working as a stress analyst for the aircraft manufacturer Henschel-Flugzeug-Werke. The German aircraft industry was expanding at a furious pace, in violation of the Versailles Peace Treaty. Only 2 years earlier, Adolf Hitler had been elected chancellor, assuming dictatorial powers, and the country was on the brink of war. Zuse's work at Henschel consisted of supervising the structural calculations needed to correct the wings of aircraft with a full metal fuselage.

Zuse remained in his position at Henschel for less than a year before resigning on May 31, 1936, in order to found his own company, which would be based on his design for a computing device. In early 1936, shortly before his departure, he wrote a lengthy memo entitled "Computing Machine for the Engineer" (Zuse 1936d) in which he detailed his vision of an automatic device comprising storage and processing components capable of performing extended sequences of basic arithmetic operations. Paradoxically, Zuse's brief tenure at Henschel would prove crucial for him in the years to come. Twice in his life, his superiors at the armament company helped him secure a discharge from the army, arguing both times that he was needed as an engineer, not on the battlefield.

In mid-1936, with the financial support of his parents, Zuse began building the automaton that had existed only in his notebooks. Some friends at the university helped by working for him, while others offered small monetary contributions so that he could finish what would become the Z1 machine. In 1937, he showed his machine to Kurt Pannke, a designer of special calculators (Zuse 1970), who was impressed enough to contribute 7000 Reichsmark for further development of the machine (at that time, a house on the outskirts of the city could be bought for 30,000 Reichsmark).

Pannke's financial support notwithstanding, one aspect that this book makes clear is that the most important difference between Zuse and other computer inventors working in the late 1930s was the fact that he was essentially building his machines alone, whereas in the United States, scientists like John Mauchly (Burks and Burks 1988) and Howard Aiken (Aiken and Hopper 1982) had the resources of universities, the military, or major corporations at their disposal. The logical and mechanical conception of the Z1 was entirely Zuse's brainchild.

Zuse, essentially unaware of the internal structure of calculators built at the time, started from scratch and developed an entirely new type of mechanical assembly. While existing desktop calculators were based on the decimal system and used rotating mechanical components, Zuse decided to use the binary system and metal plates that could move linearly back and forth. That is, the plates could only slide from position 0 to position 1 and vice versa. Zuse's basic mechanical component was a switch that could be "opened" or "closed" like an electromagnetic relay.

Such simple mechanical elements were all that was needed for a binary machine, but important obstacles had to be overcome. It was necessary to specify the complete logical description of the machine and then "wire" it accordingly. The mechanical