Konrad Zuse's Computer Z3

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Berlin, April 2016

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1 Introduction

Konrad Zuse was born in Berlin, Tübingerstr. 2 on 22 June, 1910 and died on December, 18, 1995 in Hünfeld close to Fulda. In Hünfeld he was living from 1956-95.

In 1929 Konrad Zuse enrolled at the Technical High-School (Technical University), in Berlin-Charlottenburg and began his working career as a design engineer (Statiker) in the aircraft industry (*Henschel Flugzeugwerke*) and by 1935 he graduated with a degree in civil engineering. He remained in Berlin from the time he finished his degree until the end of the war in 1945, then he fled to Hinterstein/Allgäu in the South of Germany.
At the beginning of the 30s, while studying civil engineering in Berlin, he decided to develop and build bigger calculating machines, more suitable for engineering purposes. He approached the problem from various angles: Firstly, from a logical and mathematical point of view, this involved

1. Program control,
2. The binary system of numbers,
3. Floating point arithmetic.

Today, these concepts are taken for granted, but at the time it was a complete new machine for the computing industry.

Secondly, from the design angle

1. Allowing fully automatic arithmetical calculation,
2. High-capacity memory,
3. Modules or relays operating on the yes/no principle.

Konrad Zuse started in 1934, working independently and without knowledge of other developments going on around him. He had not heard of Charles Babbage when he started his work. At that time, the computing industry was limited to mechanical calculators using the decimal system. Punched card devices were slightly further developed and able to deal with relatively complex operations for statistical and accounting purposes. However, these machines were almost entirely designed for commercial application. This meant that mathematicians and engineers had to develop computers on their own, working independently from one another.

His research was initially aimed at pure number calculation, but soon led on 1935/36 to new ideas about *computing* in general. He started data processing with the yes-no status, today we say bit.

Konrad Zuse defined 1936 *computing/rechnen* as

The formation of new data from input according to a given set of rules.

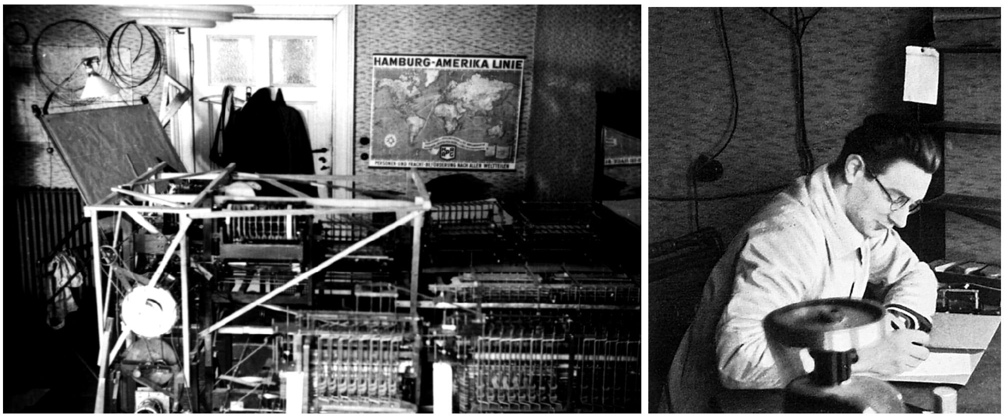
This basic theory meant that all computing operations could be carried out by two status elements, for example by relays operating according to the dual status principle. The most suitable devices available at the time were telephone relays, but he used for the Z1 an another solution for financial reasons, namely thin metal sheets.

As an civil engineer (civil engineering) he had no idea of the existence of such a discipline. He developed a system of conditional propositions for relays and called it *Aussagenkalkül.* Today it is called as Boolean algebra. His former mathematics teacher showed him that this sort of calculation was identical with the propositional calculus of mathematical logic.

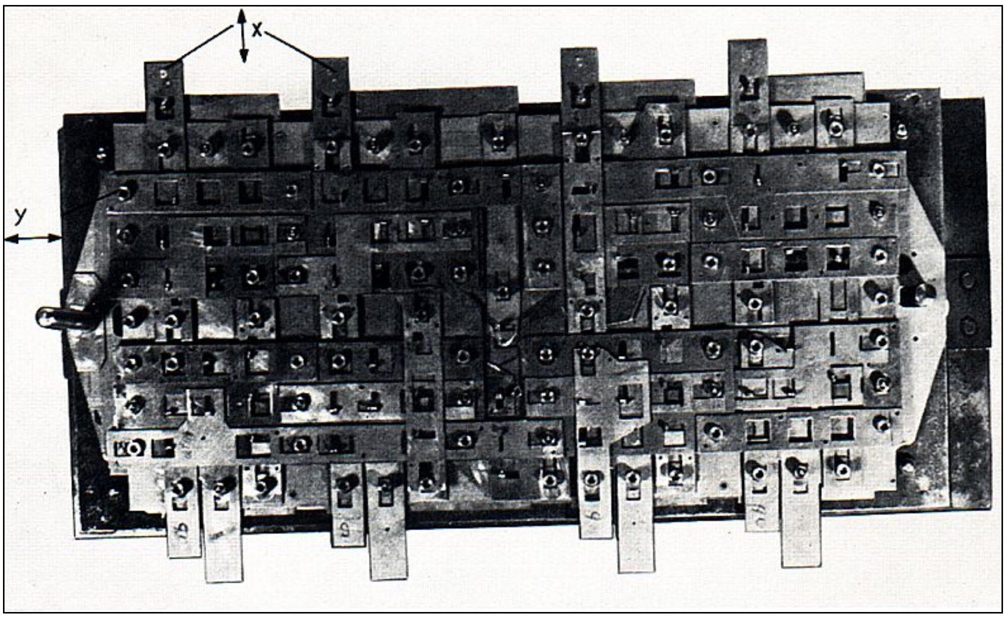
He started to build the Z1 in the living room of his parents 1936 in Berlin-Kreuzberg. Till 1945 the computers Z2, Z3 and Z4 followed. Additionally he built the S1, a special Z3, but much smaller and not programmable, especially for the Henschel aircraft company.

2 History of Zuses Z1, Z2, Z3 and Z4

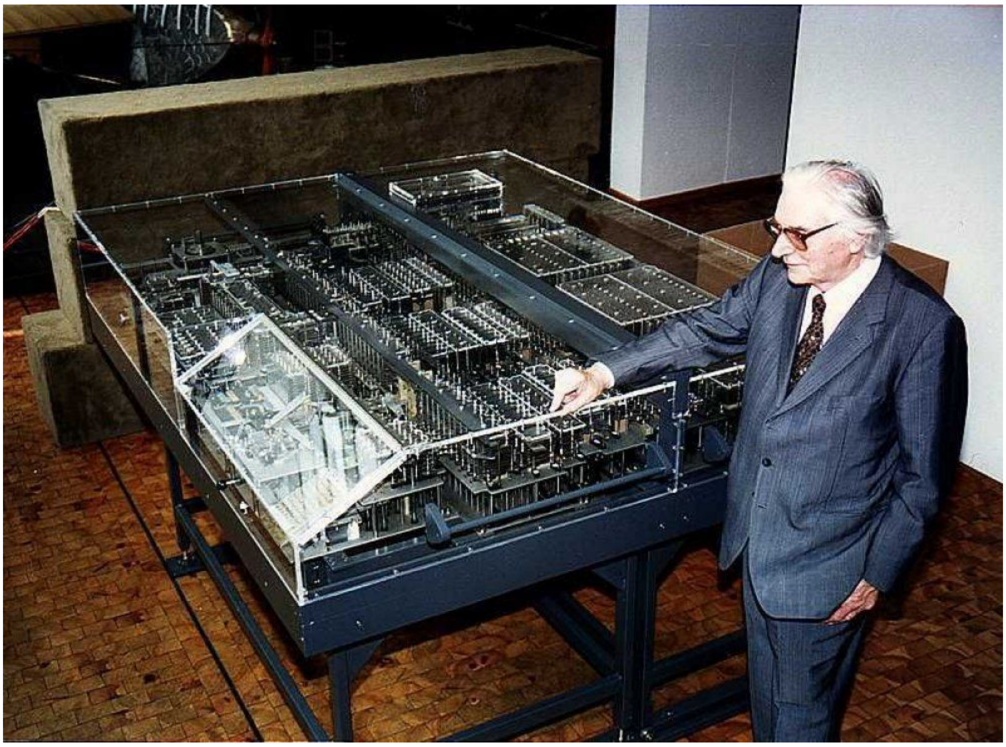
During 1936 to 1938 Konrad Zuse developed and built the first binary digital computer in the world, the Zl. A copy of this computer is on display in the *Deutsche Technik Museum Berlin* since 1989.



Picture 1: The Z1 (1938) in the living room of his parents in the Wrangelstr. 37 in Berlin-Kreuzberg and Konrad Zuse ca. 1935.



Picture 2: A design of logical circuits, realized with thin metal sheets. Using metal sheets he could build the OR, XOR, AND und the NEGATION circuits.


Picture 3: The reconstructed Z1 (1987-89), today in the Deutsche Technik Museum Berlin on display.

The Z1 did not work reliable, because the thousands of metal sheets were constructed with a jigsaw. The memory did work, however mainly the adder made a problem. The reason was the very elegant construction of the lookahead, however too much metal sheets had to be move in one cycle.

While the Z1 was realized with thousands of thin metal sheets, Konrad Zuse used for the Z2 relays and the mechanical memory of the Z1. The Z2 was a test with a small pilot machine in order to use relays. He used about 200 relays operating with 16 bits on the basis of fixed-point arithmetic and the mechanical memory of the Z1 with only 16 words.

The first fully functional program-controlled electromechanical digital computer in the world, the **Z3** was completed by Konrad Zuse on May 12, 1941, but the machine was destroyed on December 21, 1943 during the war. Because of its historical importance, a copy was build in 1961 and put on display in the *German Museum (Deutsches Museum Munich*) by Konrad Zuse. Two further reconstructions follwed in 2001 and 2010.

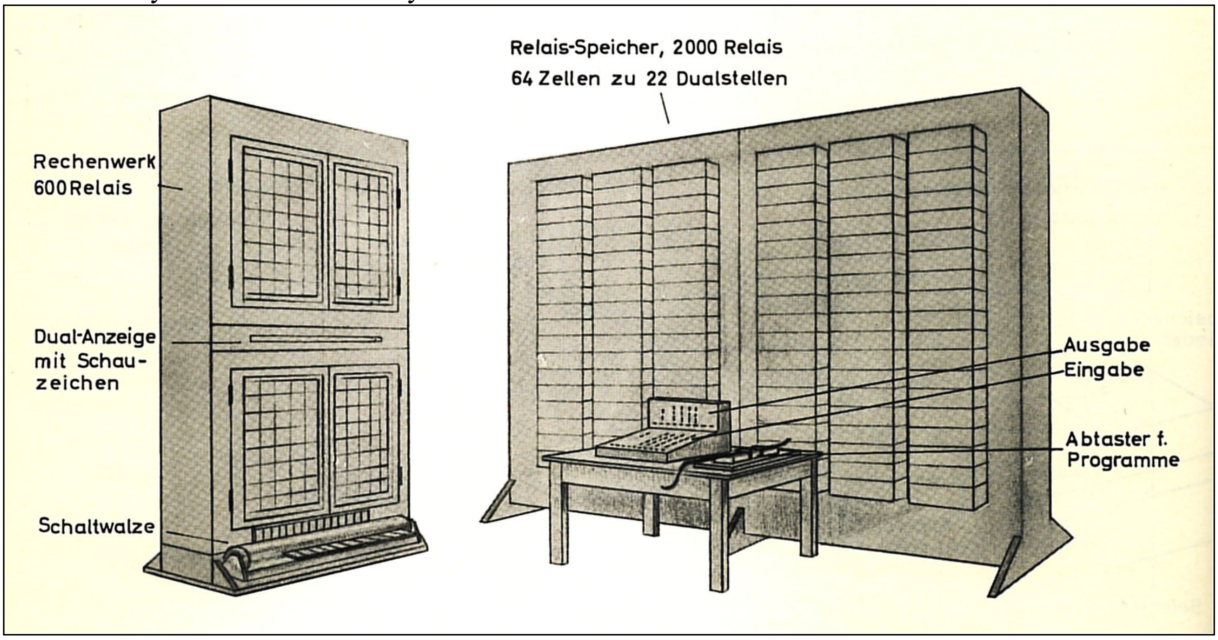
Then Konrad Zuse built the more sophisticated Z4, which was the only Zuse Z-machine which survived the war. The Z4 was almost complete when, due to continued air raids, it was moved from Berlin to Göttingen where it was installed in the laboratory of the *Ärodynamische Versuchsanstalt (DVL/Experimental Aerodynamics Institute*). It was only there for two weeks before Göttingen was in danger of being captured and the machine was once again moved to a small village Hinterstein in Allgäu/Bavaria (April 1945). Finally it was moved to Switzerland where it was installed in the ETH in Zürich in 1950. It was used in the Institute of Applied Mathematics at the ETH until 1955 by Eduard Stiefel.

3 History of the Zuse S1

The Zuse S1 was a special machine, not programmable and was constructed for purposes of the Henschel Aircraft Company in 1941. These were two machines which really worked during the second war till 1943.

4 Zuse Z3

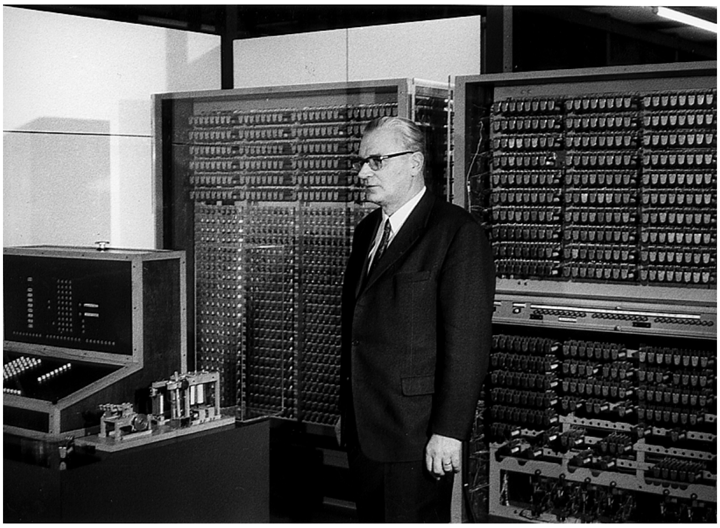
Konrad Zuse built the machine Z3 from 1939 to 1941 in the Methfesselstraße 7 in Berlin-Kreuzberg with some friends and a small support by the government. With the Z3 Konrad Zuse wanted to show, that it is possible to build a reliable working machine for very complicated arithmetic calculations, which is freely programmable and is based on a binary floating point number and switching system. For reliability reasons he used relays for the entire machine.

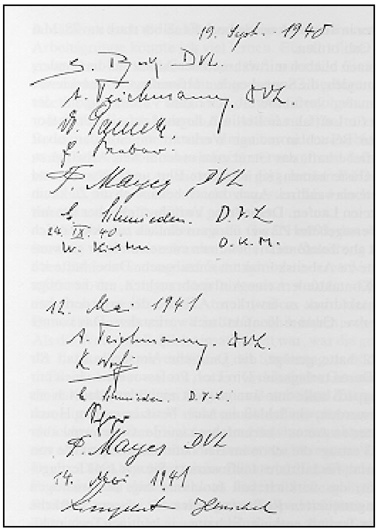


Picture 4: The design of the Z3 by Konrad Zuse in 1939. There does not exist a photo of the Z3 because all documents and photos were destroyed by allied air raids during the war at December 21, 1943. We give a translation of the German text on the image: ***Rechenwerk 600 Relais***: The arithmetic unit consists of 600 relays**.** ***Dual-Anzeige mit Schauzeichen***: Arithmetic unit with a display of the registers R1 and R2 with an indicator. ***Schaltwalze:*** The clock frequence generator. ***Relais-Speicher, 2000 Relais, 64 Zellen zu 22 Dualstellen***: The memory consisting of 2000 relays, 64 words, each word had 22 bits. ***Ausgabe/Eingabe***: Output and input device with decimal floating point numbers. ***Abtaster f. Programme:*** The punch tape reader/the programming device, delivering nine instructions to the control unit of the Z3. The control unit is mainly situated in the arithmetic unit. Konrad Zuse rebuilt the Z3 in 1960/61 in his Zuse KG[1] in order to show the performance of this machine to the patent justice and to demonstrate this machine for advertising purposes.

Picture 5: The Methfesselstr. 7 in Berlin Kreuzberg. Behind the wall at the right side of the entrance the Z3 was constructed. The door is in the wall between the both cars.

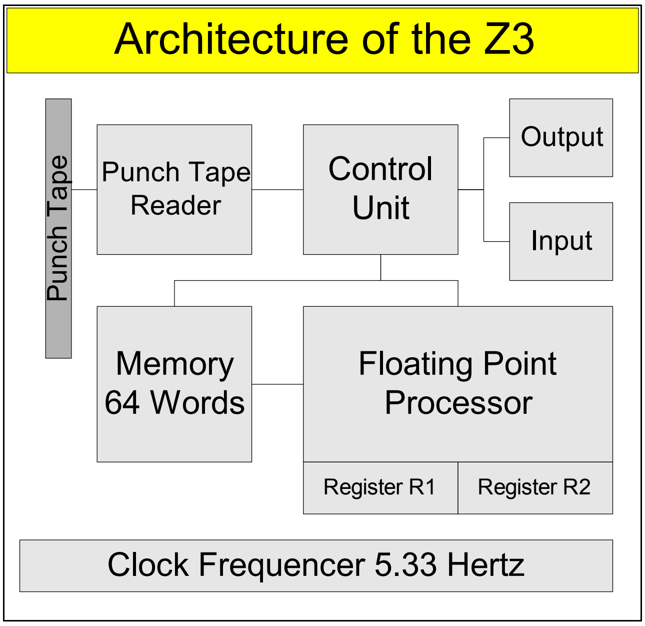
[1] The Zuse KG was founded in 1949 in Neukirchen (Kreis Hünfeld). This is about 120 km north of Frankfurt. In 1957 the Zuse KG moved from Neukirchen to Bad Hersfeld, which lies 15 km north of Neukirchen. The main reason were the cramped space for rooms and the production facilities.

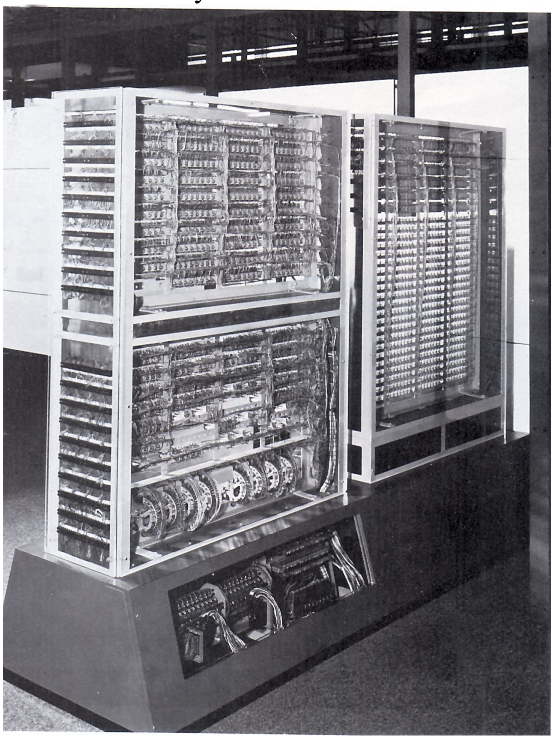




Picture 6: The rebuilt computer Z3 in 1979 with Konrad Zuse. The memory is on the left side and the arithmetic unit with the stepwise relays are on the right side, left on the front the console with the punch tape reader can be seen. Right the diary of Konrad Zuse on May 12, 1941: Konrad Zuse presented the working Z3 to scientists in Berlin (DVL*, German Aircraft Research Institute in Berlin-Adlershof /Deutsche Versuchsanstalt für Luftfahrt*). Only five scientists saw the working Z3, no press was there.

The Z3 was freely programmable, based on a binary floating number and switching system. It was a really working computer. Interesting to mention is: the Z3 did not store the program in the data memory, the memory for the program was a punch tape. The Z3 contained in 1941 almost all the components of a modern computer as required by John von Neumann et al. in 1946 /BURK46/. One exception was the ability to store the program in the memory together with the data. Konrad Zuse did not implement this feature in the Z3 because the memory of 64 words was too small for this. He wanted to calculate thousands of instructions in a meaningful order. The machine he constructed should be freely programmable. For this reason, he only used the memory for values or numbers.





Picture 7: The block structure of the Z3 and the rebuilt machine Z3. The block structure of the Z3 is very similar related to a modern computer. The Z3 disposed of separate units, like punch tape reader, control unit, floating point arithmetic unit and input- and output devices. The reeigsiers R1 and R2 contain the operands.

Burks et al. /BURK46/ wrote as late as in 1946: *In as much as the completed device will be a general-purpose computing machine it should contain 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, i.e. independent of the human operator after the computation starts.* It is important to notice, that the Z3 contained organs like an arithmetic unit, memory-storage, control and connection with the human operator. The machine Z3 contained a special operating modus. With the instruction *Lu* the input device was activated and the program was stopped. The human operator could check, among others, the Registers R1 and R2 of the arithmetic unit and he could make intermediate calculations using the Registers R1 and R2. Then he could proceed the program. This is a very early interactive communication with the machine, it is an interesting ergonomically principle. This is exactly what Burks proposed, but **ten** years later.

4.1 Basic Specifications of the Z3

The Z3 consists of

1. A binary number system,
2. Floating point arithmetic,
3. 22-bit word length, with 1 bit for the sign, 7 exponential bits and a 14-bit mantissa,
4. 2,600 relays, 600 in the arithmetic and program section and 2000 in the memory,
5. Programming device,
6. Decimal input- and output device,
7. Arithmetic exception handling.

The calculations possible were addition, subtraction, multiplication, and division, taking the square root, as well as some ancillary functions. The construction of the machine was interrupted in 1939 when he was called up for military service. It was typical of the attitude prevalent in Germany at that time that he should be later released from active service, not to develop computers, but as an aircraft engineer.

However, in his spare time and with the help of friends, it was possible for him to complete the machine. By May, 12, 1941 the Z3 was working and presented to the aircraft construction authorities. The *German Aircraft Research Institute* in Berlin-Adlershof *(DVL/Deutsche Versuchsanstalt für Luftfahrt*) showed greatest interest. Professor Teichmann, who had been working on the problem of wing flutter, was particularly attracted. Unlike aircraft stress, wing flutter results in critical instability due to vibration of the wings, sometimes in conjunction with the tail unit. Complex calculations were needed in order to overcome this design problem. The most difficult part was calculating the so-called *Küssner determinants* based on complex numbers and unknown quantities in the main diagonal. Konrad Zuse achieved a breakthrough using his equipment for this calculation. Unfortunately the Aircraft Research Institute had not been given a high enough priority for Konrad Zuse to release him from military service. Only Professor Herbert Wagner, who was working on the development of remote-controlled flying bombs, and for whom he worked as a stress analyst, was in this enviable position.

However, Wagner was very understanding, and helped as much as possible by allowing Zuse to use some of his work time on his project. By then Konrad Zuse founded his own small engineering business, the *Zuse-Ingenieur-Apparatebau* in Berlin (1941). Later the Z3 was destroyed after bombing raids (1943). Because of its historic importance he did rebuilt the Z3 20 years later; a replica now is displayed in the German *Museum in Munich* (*Deutsches Museum München*).

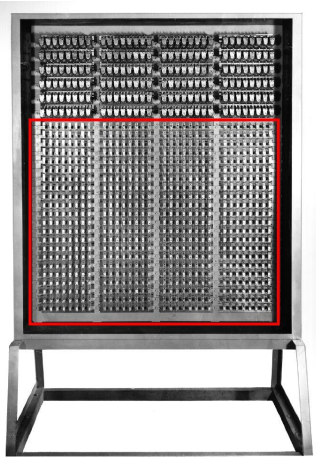
4.2 Components of the Z3

The Z3 consists of the following components.

Parallel Machine
The Z3 was a parallel working machine. The 22 bits from the memory of the Register R1 and vice versa were moved in one step (cycle). The same holds for the binary arithmetic unit, where, among others, two parallel adders (exponent, mantissa) were used.

Control Unit
This unit interpreted the orders on the punch tape, in order to enforce the necessary operations, like addition, multiplication, etc.

Memory
The memory of the Z3 consisted of 64 words à 22 bits. Each word was directly addressable by the instructions Pr z or Ps z, where z is the address in the range: $1 \leq z \leq 64$. For each bit/ (yes-no status) a relay was needed (See the image). The six upper rows show the multiplexer (Wählwerk) to select the address in the memory by only six instructions from the punch tape.



Floating Point Numbers
Konrad Zuse described in 1934 the concept of a floating processor and implemented in 1936 such a floating point processor. This is ten years before Burks et al. /BURK46/ postulated it as a concept for modern computers (not a built machine). Konrad Zuse also implemented a powerful arithmetic exception unit.

Let us consider the discussion of floating point numbers in the paper of Burks et al. /BURK46/ more precisely: *It would therefore seem to us not at all clear whether the modest advantages of a floating binary point offset the loss of memory capacity and the increased complexity of the arithmetic and control circuits.* In /NEUM45/ the use of the binary system for computers is proposed. It is very important to notice, that floating point numbers were discussed as late as in 1946 by Burks et al. and they were not really convinced that this is a good concept. Konrad Zuse realized it already with the Z1 in 1936.

Instruction Set
The Z3 had nine instructions given by a punch tape. The Z3 disposed of the following instruction set and cycles, we introduce the following notation: R1 and R2 are Registers à 22 bits. The notation: R1:= R1 + R2 means: The contents of Register R1 is added to the content of Register R2 and the result is stored in Register R1. Register R2 is set to empty after the arithmetic operation.

Instruction	Function	Cycles
Pr z	To read the contents of the memory cell z and write it into the Registers R1	1
Ps z	To write the contents of Register R1 in the memory cell z.	0-1
Ls1	Addition: R1 := R1 + R2	3
Ls2	Subtraction: R1 := R1 - R2	4-5
Lm	Multiplication: R1 := R1 x R2	16
Li	Division: R1 := R1 / R2	18
Lw	Square root: R1 := SQR(R1)	20
Lu	To call the input device for decimal numbers.	9-41
Ld	To call the output device for decimal numbers.	9-41

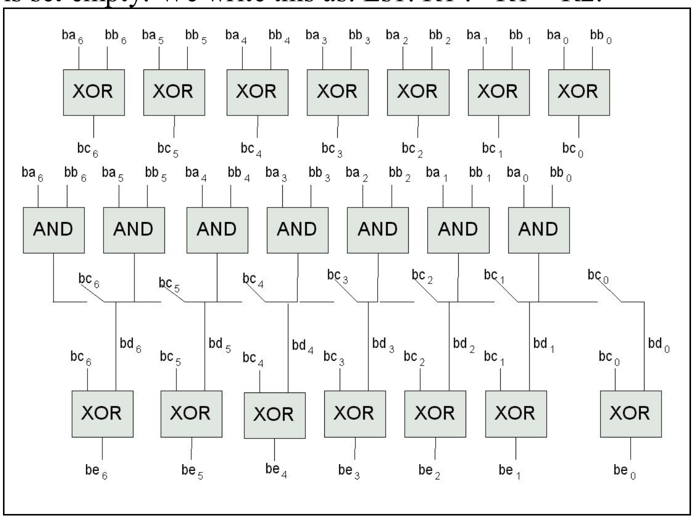
Conditional Branch
It is a little bit surprising, that the conditional branch is missing. Konrad Zuse described in his papers from 1936 till 1945 a lot of scientific and numerical problems, which he wanted to solve with his machines. For this calculations he did not need the conditional branch. In /ZUSE36/ and /ZUSE37a/ he mentioned the possibility to store instructions in the data memory. However, in 1944, he mentioned the conditional branch indirectly in the context of free programs /ZUSE45/, p16. Konrad Zuse introduced *Free Programs (Freie Rechenpläne)*: The definition is: *Bei den freien Rechenplänen beeinflussen die eigentlichen Variablen den Ablauf der Rechnung. Zunächst können die bei den quasistarren Rechenplänen besprochenen Planvariablen wie variable Operationszeichen, Strukturzeichen usw. Funktionen der eigentlichen Variablen sein. Es kann z.B. die Art der Operation in einer Rechengleichung erst errechnet werden.*

Translation: *With the free programs the actual variables influence the execution of the calculation. First of all the variables, like operation signs, structure signs, as defined with the quasi rigid (quasi starr) programs, etc., can be functions of the actual variable. It is, for example, possible to calculate the type of operation in a calculation equation.*

Arithmetic Unit and Lookahead

The arithmetic unit of the Z3 is Konrad Zuses masterstroke. The two basic arithmetic operations of the Z3 are the addition and subtraction of the mantissa, exponent and signs. Addition and subtraction require more than one cycle because, in the case of floating point numbers, care has to be taken to set the size of the exponent of both arguments to the same value. This requires some extra comparisons and shifting. The number of cycles needed for the Lu and Ld instructions varies, because it depends on the exponent of the argument. A number can be stored in memory (Ps) in zero cycles when the result of the last arithmetic operation can be redirected to the desired memory address. In this case, the cycle needed for the store instruction overlaps the last cycle of the arithmetical operations.

Konrad Zuse used a self developed *carry look-ahead* circuit of relays for the addition and subtraction of floating point numbers. With this concept he could add two floating point numbers in three cycles. Assuming the numbers to be added were still in the memory, then he needed five cycles, two for the instructions Pr and three for the instruction Ls1. With the first cycle, the first operand was transferred to Register R1 and with the second cycle, the second operand was transferred to Register R2. Then, the exponent and mantissa were added and the result was stored in Register R1. After this Register R2 is set empty. We write this as: Ls1: R1 := R1 + R2.



Picture 8: The design of the adder of the Z3. ba is the first and bb the second operand, i.e. ba0 is the first bit of ba. The result is be. These are three internal registers. From the view of the author it is a very elegant combination of a so-called Half- und Full-Adder. The number of cycles is independent from the size of the numbers, means the number of bits. This is a very elegant design.

The multiplication algorithm of the Z3 is like the one used for decimal multiplication by hand, that is, it is based on repeated additions of the multiplicator according to the individual digits of the multiplicand. The division algorithm is similar to the multiplication one, but the repeated substraction is used. The instruction algorithm behind the instruction Lw is a jewel of the Z3. The main idea is to reduce the square root operation to a division.

Arithmetic Exception Handling

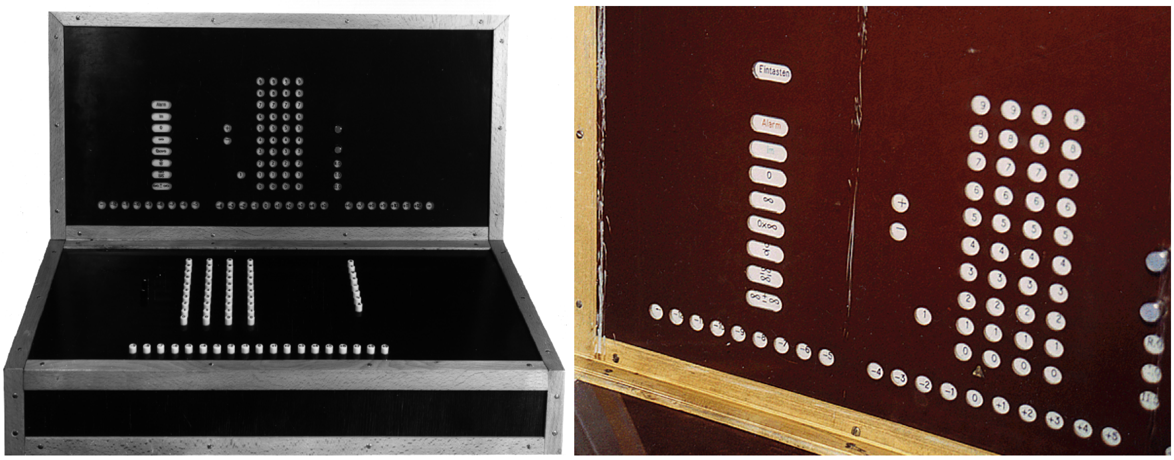
The Z3 disposed of an arithmetic exception handling. Konrad Zuse implemented the exception handling because he wanted to be sure that the Z3 calculates the numbers correctly even when the Z3 is working without a supervisor. The Z3 recognized the following operations:

- Underflow of the range of numbers is: 0.
- Overflow of the range of numbers is: ∞.
- For the calculation with 0 holds: $0 + x = x$, $0 * x = 0$, $x / 0 = \infty$, $0 / 0 = ?$
- For the calculation with ∞ holds: $\infty + x = \infty$, $\infty * x = \infty$, $1 / \infty = 0$.

- All operations with ? have the result ?.
- 0/0 = undefined
- ∞-∞ = undefined
- ∞/∞ = undefined
- 0 x ∞ = undefined

Input- and Output Devices

The undefined state was shown on the output device on the left side with small lights. For the numbers 0 and ∞ Konrad Zuse used special bit codes in the exponent. An exponent of –64 is the decimal 0. An exponent of –63 or +63 represents ±∞. The Z3 calculates always correctly, if an argument is 0 or ∞ and the other argument is in the allowed range.

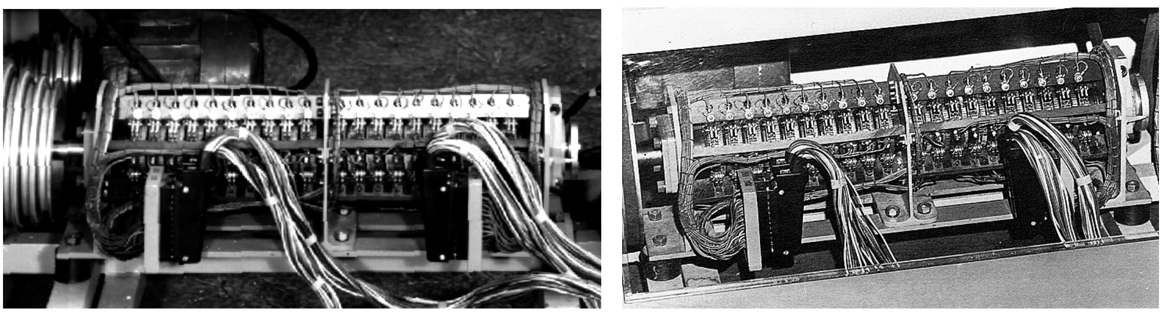


Picture 9: The input- and output devices of the Z3. At the front the numbers could be put in by buttons. There were four buttons for the mantissa and 17 buttons for the exponent (from -8 to +8). The results were shown by lamps. Right: The output device of the Z3 with the lamps for the decimal numbers (right) and the arithmetic exception handling on the left side.

The binary floating point numbers were converted to decimal floating numbers. For this conversions the Z3 needed between 9 and 41 cycles depending on the exponent. The mantissa consisted of four decimal digits and the exponent was between –8 and +8. The biggest positive decimal number which could be shown was $9999*10^{8}$, the lowest negative number was $-9999*10^{-8}$, but internally the Z3 could work with numbers 10^{20} till 10^{-20}, of course in the binary system.

Clocked Maschine/Clock Frequency

The Z3 is a clocked machine. Konrad Zuse used this principle to synchronize the different components of the machine. In order to do this he implemented a special impuls generator with a drum.



Picture 10: The impulse generator for the Z3. The speed of the capstan could be controlled in steps. It is an electric motor which drives a shaft, upon which are attached a number of arms (or protruding levers), where each arm is used to close a switch, and the angular separation between the arms caused different switches to be closed at different times, thereby allowing the system to control the flow of data between the various units.

The impulse generator stepwise provides the different relay groups with electrical power. The clock frequency was around 5,3 Hertz depending on the quality of the telephone relays, so the faster the clock then the faster the machine. Konrad Zuse mentioned that a multiplication of two floating point numbers took about three seconds. The Z3 needed 16 cycles for a multiplication. For this reason the clock frequency is 16 / 3 ≈ 5.3 Hertz. In order to avoid sparking of the relay contacts when switching them, he used the drum to drop off the electricity at the switching time. This principle avoided material rust and guaranteed a long functionality of the relay contacts.

An Example Program (Polynomial)
We now present an example program of the Z3. We want to calculate the polynomial: ((a4x + a3)x + a2)x + a1. The numbers for a4, a3, a2 and a1 are already stored in the memory cells 4, 3, 2, 1, which had to be done by the input device. The number for x is required by the input device with the instruction Lu.

Lu	To call the input device for the variable x.
Ps 5	To store variable x in memory cell 5.
Pr 4	Load a1 in Register R1.
Pr 5	Load x in Register R2.
Lm	Multiply: R1 := R1 x R2.
Pr 3	Load a3 in Register R2
Ls1	Add: R1 := R1 + R2.
Pr 5	Load x in R2.
Lm	Multiply: R1 := R1 x R2.
Pr 2	Load a2 in Register R2.
Ls1	Add: R1 := R1 + R2.
Pr 5	Load x in Register R2.
Lm	Multiply: R1 := R1 x R2.
Ppr 1	Load a1 in Register R2.
Ls1	Add: R1 := R1 + R2.
Ld	Shows the result as a decimal number.

After the execution of the program the Z3 stopped and showed the result via the instruction Ld.

Minimal Design Principle and Universal Computer (Turing)
Konrad Zuse followed a minimal design principle with the construction of his computers. He tried to build a powerful computing machine with minimal effort and costs. He had no other way because his parents were not rich and he had not much money. For Konrad Zuse, the Z3 was the last machine in a series of trial machines (Z1-Z3) in order to build a machine which was able to solve the mathematical problems of engineers and scientists. Although he was convinced, that his machine could calculate all mathematical problems, he never tried to prove it. He did show this with many examples and chess. In 1941 he said to friends, that his machine can play chess. However, he had the right feeling, that his machine could calculate everything. In 1998 Raul Rojas /ROJA98a/ formulated the proof, that the Z3 is an universal computer.

From the engineering point of view, the gap between practical and pure mathematical logic was bridged in order to simplify the design and programming of computing machines. At roughly the same time in England, the mathematician and logician Alan Turing was in the process of solving this problem from a different angle. He used a very simple paper computer as a model in order to place theoretical logic on a more formal basis. Turing's work was of major importance for the theory of computer science. However, his ideas had little influence on the practical development of computing machines.

John von Neumann versus Konrad Zuse
Very often is discussed the architecture of the so-called John von Neumann-Computer and the Zuse-Computer. We state the following: In the paper /NEUM45/ John von Neumann describes the architecture of computing machines. Among others, John von Neumann proposes the principle of the separation of the units of a computer (control unit, memory, arithmetic unit, input-/output devices). He also proposes the principle of the stored program computer. However, it is very important to mention here, that Konrad Zuse **implemented** the separation of the units of a computer already from 1936-38 with the Z1. In /ZUSE36/ and /ZUSE37a/ Konrad Zuse mentions the possibility to store various things in a memory, among others, instructions.
The author refers to the very interesting discussion by Giovanni Sommaraga and Thomas Strahm /SOMM15/ about this context, especially to the chapter (p.43): *The Stored-Program Universal Computer: Did Zuse anticipate Turing and John von Neumann?*

5 Reconstruction of the Zuse Z3

From 2007 to 2011 the author did reconstruct the Z3 in the original size and called it Z3r.

Picture 11: The Z3r has the size of the original Z3 (2,20mx1,20m).

The idea of the Z3r was among others the following: What is the answer to the question

What is a computer?

The author is convinced that the Z3/Z3r is very suitable to give an answer because all elementary operations of a computer can be shown down to the bit. The authors gives each months presentations at the *Deutsche Technik Museum Berlin* for interested visitors. The author is convinced that with the Z3r it is possible to give an answer for the question: What is a computer?

6 The Zuse KG

Only the Z4 survived the war and could be rented from 1950-55 to the ETH in Zürich. In 1949 Konrad Zuse founded the company Zuse KG in Neukirchen Kreis Hünfeld close to Fulda with some friends. His idea was to build and sell computers, but Germany was destroyed by the consequences of the second world war. It was a totally crazy idea, but he had three times a great fortune in 1950. The Z4 was ordered by the ETH-Zürich (1949). Based on the Z4 Remington Rand (US) ordered 30 computers Z9 (Pipelining computers), and the Leitz company in Wetzlar/Germany ordered the Z5 for the calculation of lenses (i.e. Leica) in 1950 and paid 300.000 DM in advance.

Picture 12: The building of the Zuse KG from 1949-57 in Neukirchen Kreis Hünfeld and the company in 1964 in Bad Hersfeld with 1200 employees. However in 1964 Konrad Zuse had to give up, the power of other computing companies was too strong. From 1967 Siemens AG was the successor.

The next table gives an overview of the most important computers produced by Konrad Zuse and the Zuse KG from 1936-1971 as a consequence of the development of the Z3/Z4. In 1971 the name Zuse KG was cancelled by the Siemens AG and was protected for 30 years by the *Patent- und Markenamt in München*. Today*, Zuse* and *Konrad Zuse* are protected by the author. We also mention some machines, which were not discussed above, and we do not list every special machine, which was produced by the Zuse KG. In /ZUSE16c/ each machine of the Zuse KG is described and illustrated with a picture.

Year(s)	**Name**	**Pieces**	**Comments**
1936-1938	Z1	1	First machine of the world with a binary floating point processor, binary logic, parallel working devices, freely programmable, separation of memory, control unit, arithmetic unit, input-/output devices. Bistable mechanical building blocks, 64 words à 22 bits. Worked unreliable.
1938-1939	Z2	1	Fixed point arithmetic, 800 relays, 16 bits binary fixed point processor, mechanical memory, test model for relays..Worked reliable.
1940-1941	Z3	1	First working computer of the world with: binary logic, powerful binary floating point processor, arithmetic exception handling, 2400 relays, 64 words à 22 bits, separation of memory, control unit, arithmetic unit, input-/output devices.
1942-1945	Z4	1	Successor of the Z3, but mechanical memory with 64 words à 32 bits, 2200 relays, binary floating point processor, arithmetic exception handling, extension in 1949 for the ETH-Zürich from 1950-1955: conditional branch, call of subprograms (second punch tape reader), MERCEDES output device.
1942	S1	2	Special computer for measuring the surface of wings of airplanes, hardware wired program, 600 relays, binary principle, 12 bits word length, destroyed 1944.
1944	S2	1	Improved model S1, automatic scanning of wings with about 100 clock gauges, hardware wired programs, destroyed 1945. Propably the first process computer of the world. computer
1950-1952	Z5	1	Mandate by Leitz/Wetzlar (optical calculations, Leica lenses), extension of the Z4 with many punch tape readers and punch writer, six times faster than the Z4, binary principle, floating point arithmetic, 42 bits, biggest relay computer in Germany, first commercial computer in Germany, 300.000 DM.
1951-1955	Z7	30	Calculating punches, mandate by Remington Rand, 30 pieces, called Remington M9.
1954	Z11	48	Used for consolidation of farming, optical industry and insurance companies. It was freely programmable, had floating point processor, easily to use by pressing buttons, 120.000DM in 1960. In 1955 the program was realized by stepwise relais, from 1957 the machine was freely programmable by a punch tape.
1956	Z22	58	First electronic computer of the Zuse KG, 38 bits, fixed point arithmetic, minimal principle, magnetic drum of 8192 words, first stored program computer of the Zuse KG, very successful, 180.000DM. Competition to the IBM 650.
1958	Z23	102	First transistor computer, same logic as the Z22, three times faster than Z22, 40 bits, very successful (ca. 150.000 DM).
1962	Z25	>105	Small and very flexible computer, 18 bits word length, process control in companies, many peripheral device, 98.000 DM.
1961	Z31	7	Parallel development to the Z23, designed for commercial applications, like banks, decimal arithmetic unit, too expensive and too large, severe flop for the Zuse KG.
1961	Z64	98	Drawing machine with high accuracy (1/20 mm), controlled by punch tapes, used for graphical representation and in the optical industry.
1965	Z43	>100	Modern transistor computer, TTL logic.

Table 1: A small list of the computers produced by Konrad Zuse and the Zuse KG from 1936-1969.

The company Zuse KG produced from 1949 to 1971 more than 800 computers.

The rebuilt Z1 is displayed in the *Deutsche Technik Museum* in Berlin-Kreuzberg. The rebuilt Z3 (1961) and the original Z4 (1945) are on display in the *Deutsche Museum München*. Another reconstruction of the Z3 can be found in Hünfeld (*Konrad-Zuse-Museum*) and the third reconstruction Z3r (by Horst Zuse) is on display in the *Deutsche Technik Museum* Berlin (working and original size).

The Z11 can be visited in the *Deutsche Technik Museum* in Berlin, where also a Z23 and Z64 can be seen. A working Z11 can bee seen in the *Konrad-Zuse-Museum* in Hünfeld close to Fulda.

Literatur

Some of the referenced literature of Konrad Zuse were not published in journals. The reason was the political situation in Germany from 1933 and the post war area.

/BAUE98/ Bauer, Friedrich, L.: Wer erfand den Neumann'schen Rechner? Informatik Spektrum, April 98, pp. 84ff.
This is an article written in the German language where F.L. Bauer discusses the dispute of the invention of the stored program computer.

/BURK46/ Burks, A.W.; Goldstine, H.H. Neumann, John von: Preliminary Discussion of the Logical Design of an Electronical Computing Instrument, 1946. In: Taub, A.H. (Editor), Collected Works of John von Neumann, Vol. 5, New York, Macmillan, 1963, pp. 34-79. Also in Randell von 1973 /RAND73/, pp. 371ff.
This is the article from 1946 where the basic principles of a computer are explained. Here, the separation of the control unit, arithmetic unit, memory and input- and output devices are required. Burks et al. also propose to store the program together with the data in the memory. However, Konrad Zuse implemented the separation of the different units of a computer already in 1938 with the Z1 and in 1941 with the Z3. It is correct, that Konrad Zuses machines did not store the program in the memory of the machine. However, Konrad Zuse mentioned this possibility already in 1936/37 /ZUSE36/, /ZUSE37a/.

/GILO97/ Giloi, Wolfgang, K.: Konrad Zuse's Plankalkül: The First High-Level "non von Neumann" Programming Language. IEEE Annals of the History of Computing, Vol. 19, No. 2, 1997.
In this article Giloi describes the fundamental ideas of Konrad Zuses Plankalkül and points out that this proposal is much closer to Prolog than to the imperative languages.

/IEEE85/ IEEE: IEEE Standard for Binary Floating Point Arithmetic (ANSI / IEEE Std 754-1985), New York, August 1985.
This is the IEEE standard for floating point numbers from 1985. The standard also uses a semi-logarithm representation of floating point numbers. The binary floating point numbers are divided in a mantissa and an exponent. The representation of the numbers 0 and $\pm\infty$ are identical to Konrad Zuses implementations in the Z1 (1938) and the following Z-machines.

/NEUM45/ Neumann, John von: First Draft of a Report on the EDVAC. Moore School of Electrical Engineering, University of Pennsylvenia, June 30, 1945. In /RAND73/, pp. 355ff.
In this paper John von Neumann describes the architecture of computing machines. Among others, John von Neumann proposes the principle of the separation of the units of a computer (control unit, memory, arithmetic unit, input-/output devices). He also proposes the principle of the stored program computer. However, it is important to mention here, that Konrad Zuse implemented the separation of the units of a computer already in 1938 with the Z1. In /ZUSE36/ and /ZUSE37/ Konrad Zuse mentions the possibility to store various things in a memory, among others, instructions.

/POEL62/ Poel, van der: Micro-Programming and Trickology. In: Hoffmann, Walter (Editor): Digitale Informationswandler, Probleme der Informationsverarbeitung in ausgewählten Beiträgen, Braunschweig, 1962, pp. 269-2311.

/RAND73/ Randell, B. (Editor): The Origins of Digital Computers. Springer Verlag, Heidelberg, New York, 1973.
This is a very good book about the history of computing.

/ROJA97/ Rojas, Raul: Konrad Zuse's Legacy: The Architecture of the Z1 and Z3. IEEE Annals of the History of Computing, Vol. 19, No. 2, 1997.
This is a very good article of the architecture of the machines Z1 and Z3 of Konad Zuse.

/ROJA98/ Rojas, Raul: How to make Zuse's Z3 a Universal Computer. IEEE Annals of Computing, Vol. 20, No. 3, July/Sept. 1998.
Raul Rojas proves, that the Z3 was an universal computer in the sense of Turing. He also shows, that the conditional branch is not a necessary instruction for a universal computer.

/ROJA98a/ Rojas Raul (Editor): Die Rechenmaschinen von Konrad Zuse, Springer Verlag, 1998.
This is a detailed analysis of a Konrad Zuses machines Z1 and Z3 with many new details. It also contains the report of the fight of Konrad Zuse for his patents from 1938 till 1967. Konrad Zuse lost this fight in 1967.

/SCHW89/ Schweier, U. und Saupe, D.: Funktions- und Konstruktionsprinzipien der programmgesteuerten Rechenmaschine Z1, Arbeitspapiere der GMD, 321, 1988.

/SEBE96/ Robert Sebesta: Concepts of Programming Languages, Addison Wesley Publishing Company, 1996, pp. 55, 97.

In this book, among others, many details related to the Plankalkül can be found.
/SPEI98/ Speiser, Ambros: The Early Years of the Institute: Aquisition and Operation of the Z4, Planning of the ERMETH. Departement of Computer Science, ETH-Zürich, 1998.
/SOMM15/ Sommaruga, Giovanni; Thomas Strahm, Editors: Turing's Revolution - The Impact of His Ideas about Computability.
The author refers to the very interesting discussion in /SAMM15/ about this theme, especially to the chapter (p.43): *The Stored-Program Universal Computer: Did Zuse anticipate Turing and John von Neumann?*
/ZUSE36/ Zuse, Konrad: Verfahren zur selbsttätigen Durchführung von Rechnungen mit Hilfe von Rechenmaschinen. Patentanmeldung Z 23 139 / GMD Nr. 005/021 / Jahr 1936.
In this paper Konrad Zuse applies a patent, which he did not get. At this time he were in a disunion. On the one side the fight for the patent would be very expensive, on the other side he wanted to build a machine. He decided to build the machines. He also made the first time statements that a memory can store many different things, like statements, names, reference numbers, ranks, data, instructions, messages, conclusions, etc.
/ZUSE37a/ Zuse, Konrad: Einführung in die allgemeine Dyadik., 1937.
In this paper Konrad Zuse mentioned very clear, that a program can also be stored in the memory.
/ZUSE39/ Zuse, Konrad: Rechenmaschine. Bericht von Konrad Zuse als Gefreiter, 1939.
In this paper Konrad Zuse describes very clearly the architectures of his machines.
/ZUSE45/ Zuse, Konrad: Theorie der angewandten Logistik - 2. Buch. der Zuse Apparatebau Berlin, 1945.
This is a very complete work about the programming of computers with the Plankalkül. There Konrad Zuse demonstrates the powerfulness of the Plankalkül with arithmetic problems to be solved in engineer bureaus, and he demonstrates chess programs on more than 60 pages.
/ZUSE47/ Zuse, Konrad: Über die Mechanisierung Schematisch - Kombinativer Aufgaben. Zuse Ingenieurbüro Hopferau, 1947.
In this article Konrad Zuse describes his ideas of the computer development in the future. His idea is to use logistical machines, which can be used to solve the mathematical problems of engineers and scientists in the opposite to the algebraic machines, like the Z4 or Mark I of Aiken. The logistical machines should be programmed with the Plankalkül.
/ZUSE48/ Zuse, Konrad: Über den Plankalkül als Mittel zur Formulierung schematisch-kombinativer Aufgaben. In: Archiv Mathematik, Band I (1948/49).
/ZUSE69/ Zuse, Konrad: Rechnender Raum, Schriften zur Datenverarbeitung Band 1. Friedrich Vieweg & Sohn, Braunschweig (1969).
/ZUSE72/ Zuse, Konrad: Der Plankalkül. Gesellschaft für Mathematik und Datenverarbeitung. Nr. 63, BMBW - GMD - 63, 1972.
/ZUSE86/ Zuse, Konrad: Der Computer - Mein Lebenswerk. 2. Auflage, Springer-Verlag, 1986.
/ZUSE93/ Zuse, Konrad: The Computer – My Life. Springer Publisher, 1993.
This is the English translation of /ZUSE86/.
/ZUSE98/ Zuse, Horst: Konrad Zuse Multimedia Show, included a 330 pages hypertext system with more than 500 pictures and 30 videos about Konrad Zuse and his Zuse KG, 1998. Also a simulation of the Z3 is implemented and it is possible to run example programs. At this time the show is in German, the English version will be available in October 1999. The show is available by the author: http://home.t-online.de/home/horst.zuse.
/ZUSE99/ Zuse, Horst: A limited edition of oil paintings of Konrad Zuse. Internet: www.zuse.de a limited edition of seven oil paintings of Konrad Zuse from 1964 to 1995 is offered. The format of each painting is 40cm x 60 cm.
/ZUSE99a/ Zuse, Horst: John von Neumann's Computer Concepts versus Konrad Zuse's Ideas and the Machines Z1 and Z3. Internet: http://home.t-online.de/home/horst.zuse.
This is a collection of statements of Konrad Zuse related to the stored program computer.
/ZUSE99b/ Zuse, Horst: Geschichte der Programmiersprachen. Technischer Bericht 1/99, TU-Berlin, 1999. Also available in the Internet: http://www.cs.tu-berlin.de/~zuse.
This is a report about the development of programming languages, where the work of twenty pioneers is described.
/ZUSE2007/ Zuse, Horst: Konrad Zuse Multimedia Show, 2007, www.zuse.de., 2007 (also for Windows 7).
This contains a detailed description of the Zuse-Computers and the simulation of them.
Many historical movies are presented
/ZUSE2016a/ Zuse, Horst: Rekonstruktion der Z3 zur Z3r, www.zuse.de, 25 p., 2016.
The reconstruction of the Z3 to the Z3r in 2010 by the author is presented.
/ZUSE2007a/ Zuse, Horst: Konrad Zuses Werk, 124p., www.zuse.de, 2007.
The original prospects of almost all important Zuse-Computers are presented.
/ZUSE2016b/ Zuse, Horst: Die Rechenanlage Z3 - Erster Computer der Welt, www.zuse.de,

35p, 2016.
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The Z22 was a competition to the IBM 650, but much cheaper and the Zuse KG introduced the computers in the German Universities and scientific institutes.
/ZUSE2016d/ Zuse, Horst: The Computer Z3, www.zuse.de, 15p.
English language, written for the anniversary of 75 years Z3 on May 12 / 2016.

7 Author

Horst Zuse was born on November 17, 1945. He received the Diploma degree in electrical engineering from the Technische Universität in 1973 and the Ph.D. degree in computer science from the Technische Universität of Berlin in 1985. From 1975 to 1995 he was a senior research scientist with the Technische Universität Berlin. His research interests are information retrieval systems, software engineering, software metrics and the measurement the quality of software during the software life-cycle. From 1987 to 1988 he was for one year with IBM Thomas J. Watson Research in Yorktown Heights. In 1991 he published the book: *Horst Zuse: Software Complexity - Measures and Methods* (De Gruyter Publisher). In 1998 the book: *Horst Zuse: A Framework for Software Measurement* (DeGruyter Publisher) were published. Today he is a Honorary Professor with the University Cottbus.