Mechanical Monsters

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American University

Four Basic Lines

- **Konrad Zuse**, mechanical, electrical relays
- **George Stibitz**, electrical relays
- **Howard Aiken**, mechanical
- **IBM**, mechanical, electrical relays

Konrad Zuse (1910-1995)

- **First person to construct an automatically controlled calculating machine**
- born in Berlin, Germany **1910**
- Techniche Hochschule Berlin-Charlottenburg: *civil engineering*
- designed a series of special forms to *systematize* mathematical calculations

First thoughts of a “lazy” man

- **Next step**: design a ***machine*** capable of taking numbers (on punched cards) and moving them (like a crane in an arcade) to the appropriate places in his calculation diagram

- **Insight**: that once you had the ***instructions*** coded for the control mechanism, you didn’t need the form; all you needed was a ***memory***

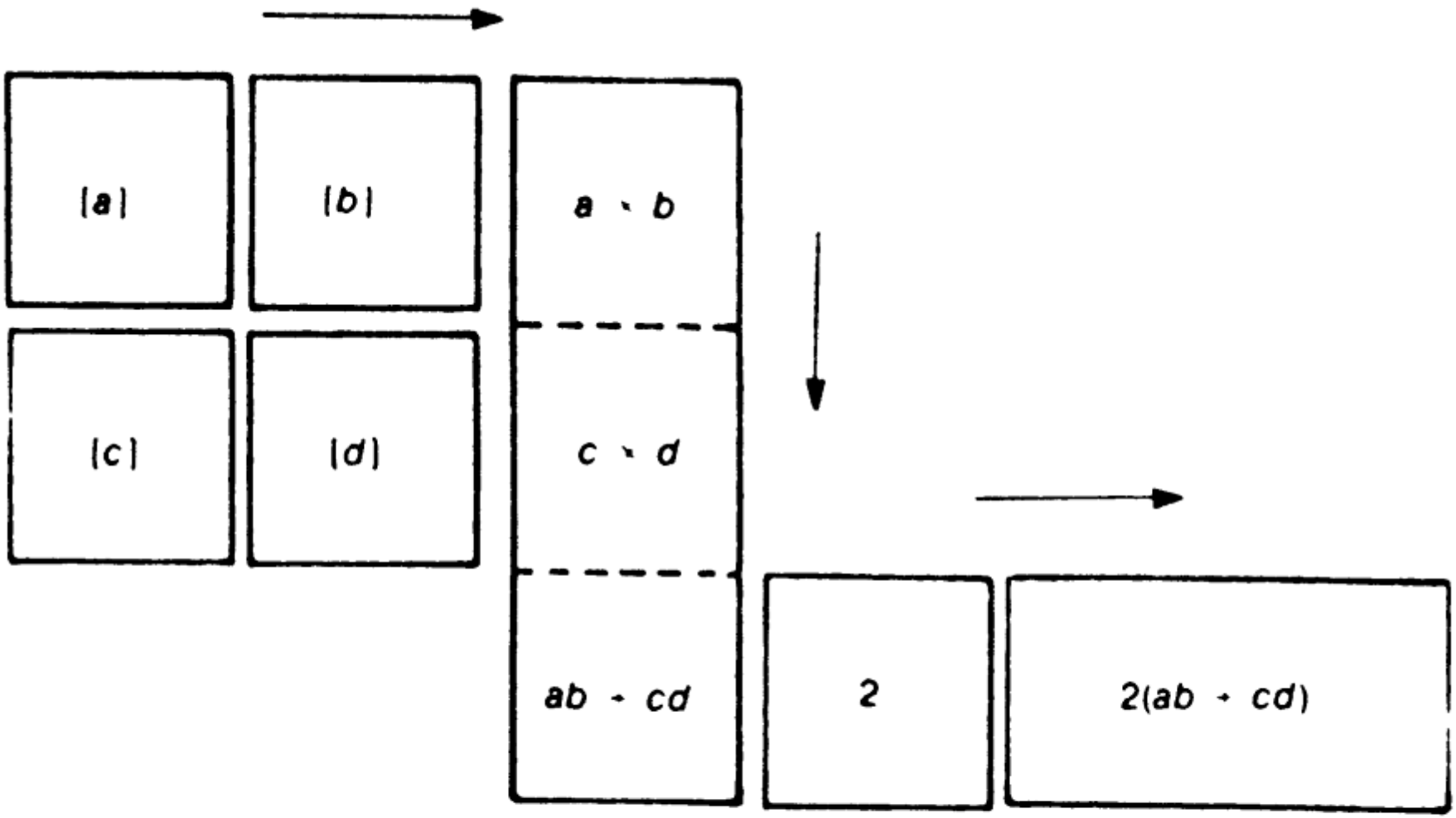


Figure 1. Graphic representation of the algebraic formula $2(ab + cd)$ (Zuse 1970, p. 36).

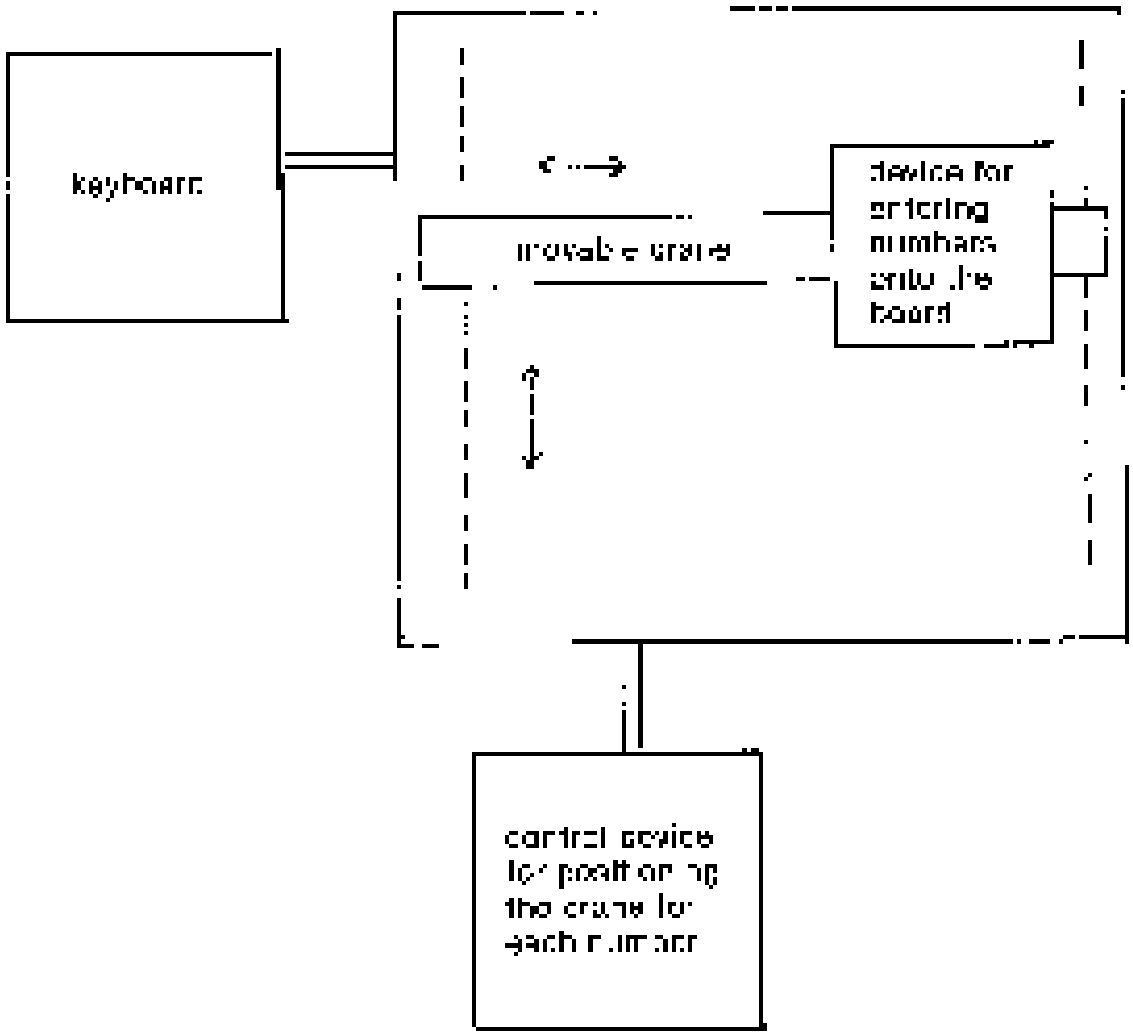


Figure 2.2. Automatic Movement of Vehicles

From ideas to action

- Plan for a calculator which would need a control, a memory, and an arithmetic unit. **1934**
- Applies for a (German) patent 1936
- Constructs the Z1 in his parents living room in Berlin **1938**
- Completes the Z2 machine 1939
- Completes the Z3: the world's **first fully automatic calculating machine** **Dec.5, 1941**

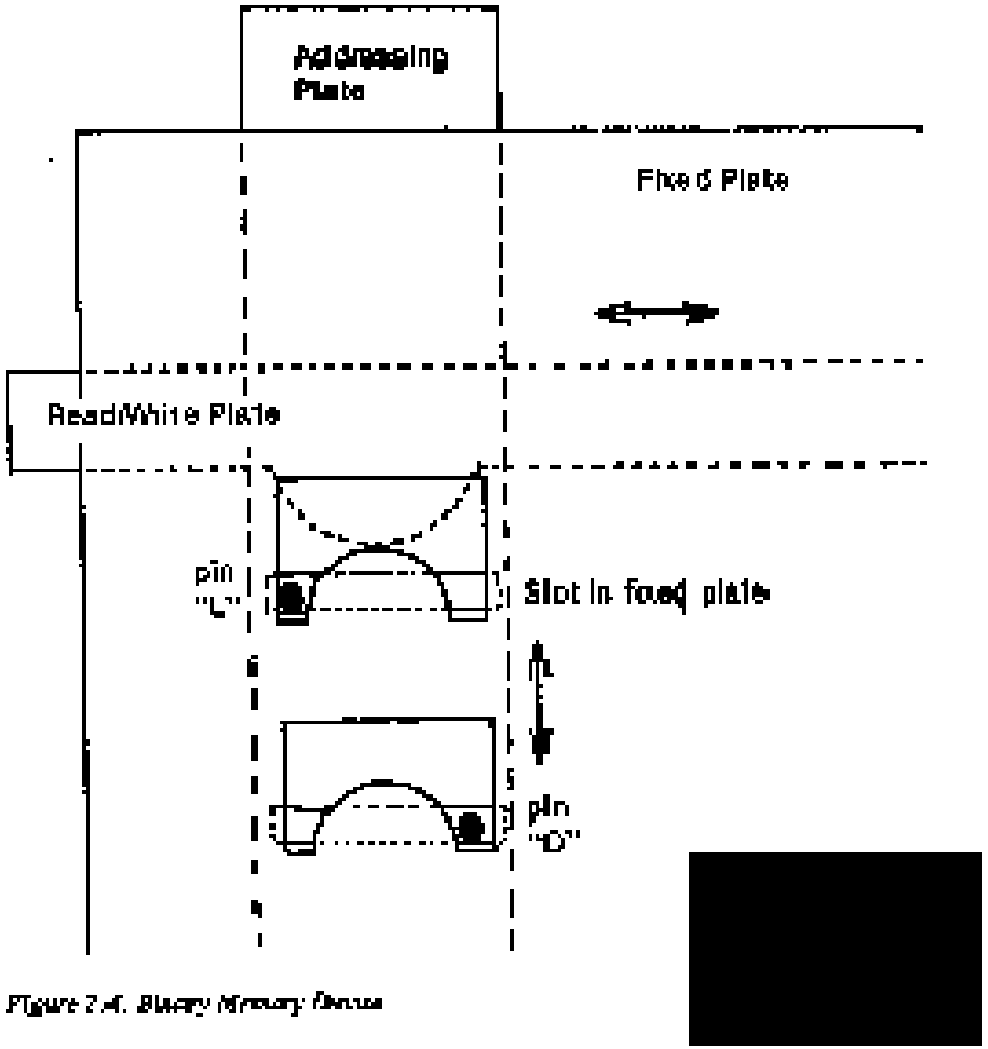
Inspiration

- 3 fundamental decisions:
  - **overall plan**: **program unit, calculating unit, memory**, and input by punched tape
  - **binary system**
  - **symbolic notation**: ***Plan Calcul*** *which is considered the world's first programming language*

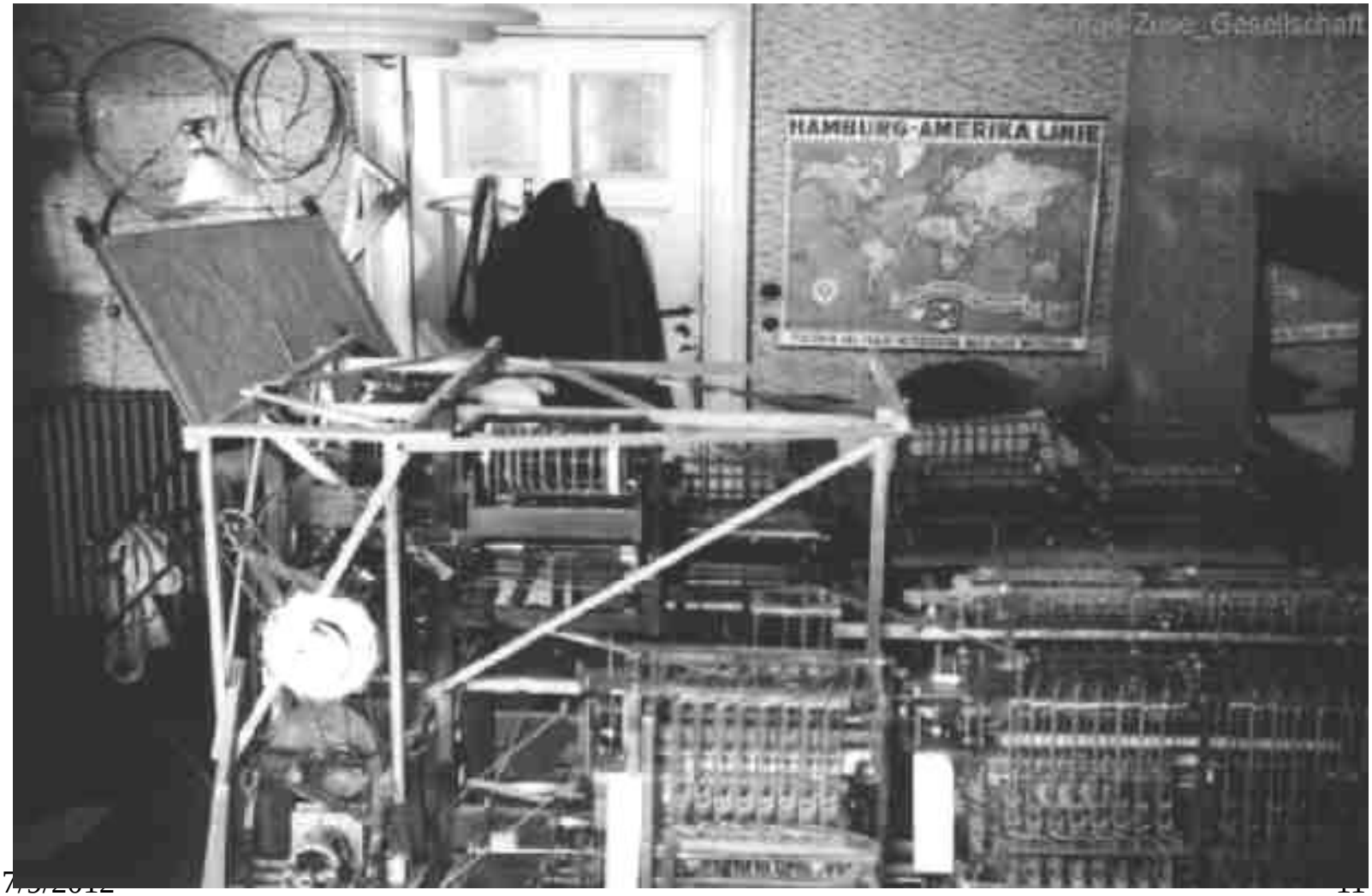
Versuchsmodell-1 Protototype)

- **Mechanical memory** capable of storing **1937**
  16 ***binary*** numbers of 24 bits each
  - **mechanical *gate* of sliding metal plates**
- **Calculating unit** used discarded ***telephone relays*** at
  - suggested by ***Helmut Schreyer***, who also suggested the use of vacuum tubes (not accepted!)
- **Control** was by hand-punched (35mm) movie film
  - *Note*: Schreyer had worked as a movie projectionist during his student days: movie projector had a mechanism to advance the film in discrete steps!

Mechanical memory (metal plates)



Z1 Relay Machine 1938



Z2 1939

- **Schreyer** builds a vacuum tube model, but their inability to get large number of vacuum tubes (valves in UK) forces them to use telephone relays
- **Zuse** is drafted into the German Army; **Schreyer** continues to experiment with ***electronic analogs*** of **Zuse's** designs, including ***neon lamps*** driven by vacuum tubes (destroyed in an air raid)
- **Zuse** demonstrates the Z2 for the ***Deutche Versuchanstalt fur Luftfarht*** (German Aeronautical Research Institute); they agree to finance the Z-3!

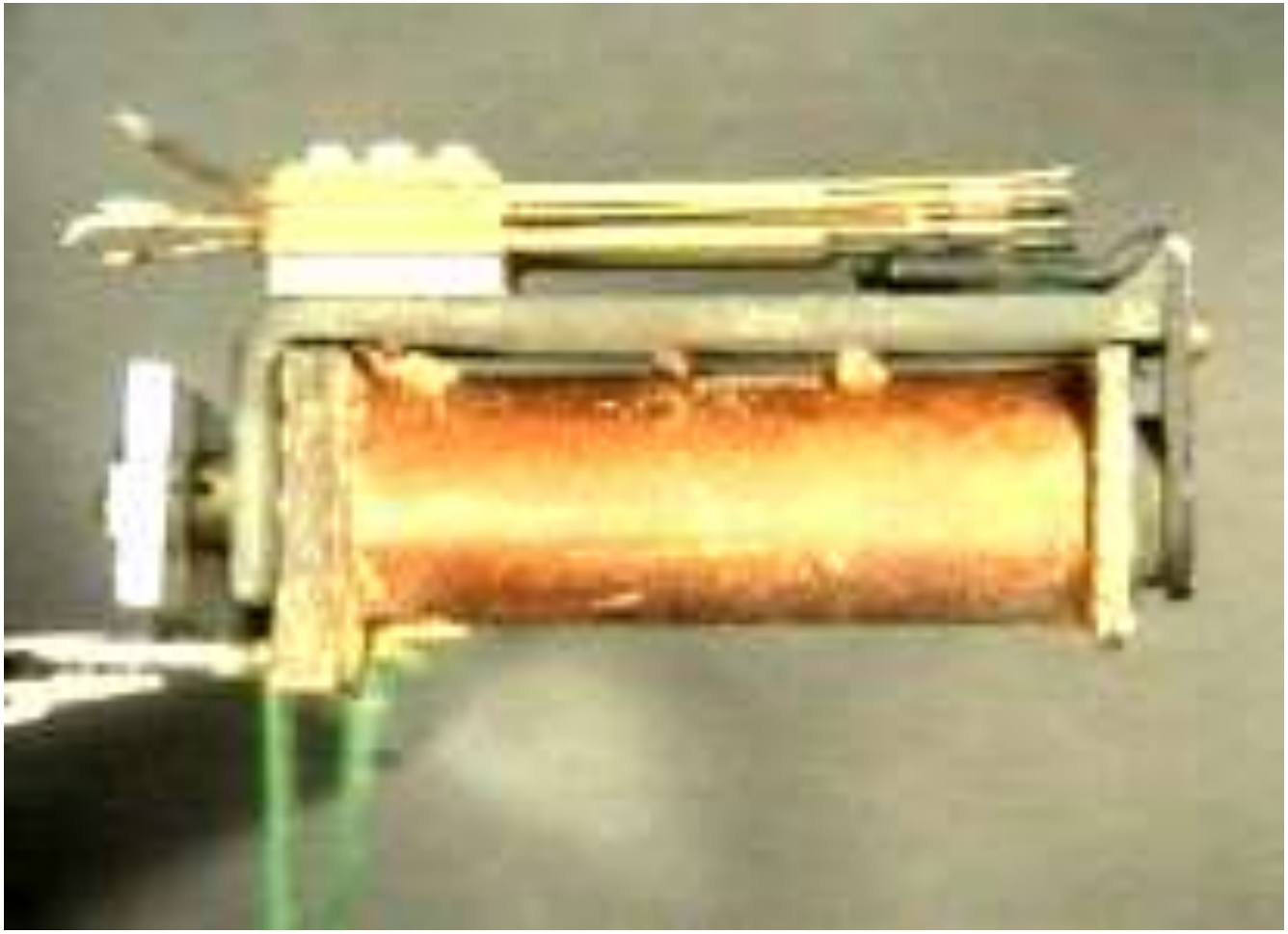
Zuse's Z-3

- **First *fully operational calculating machine* with *automatic control* of it's operations.**
- **Electromagnetic relays:**
  - **1400 memory**
  - **600 arithmetic**
  - **600 miscellaneous functions**

  2600 total

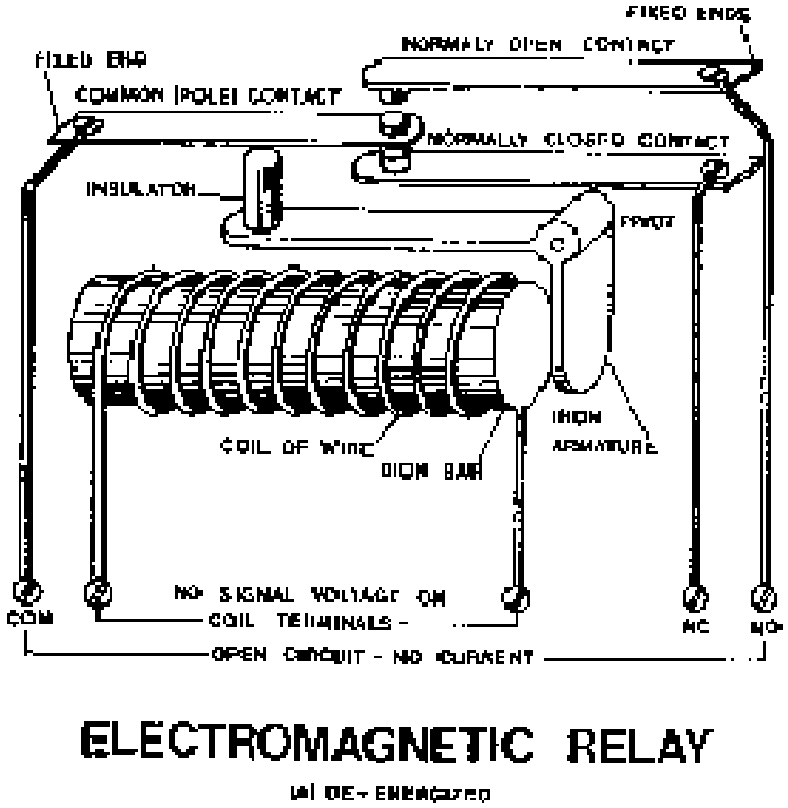
  also 20 step switches

Relay of the type used in the Z3



Relay(from Ceruzzi)

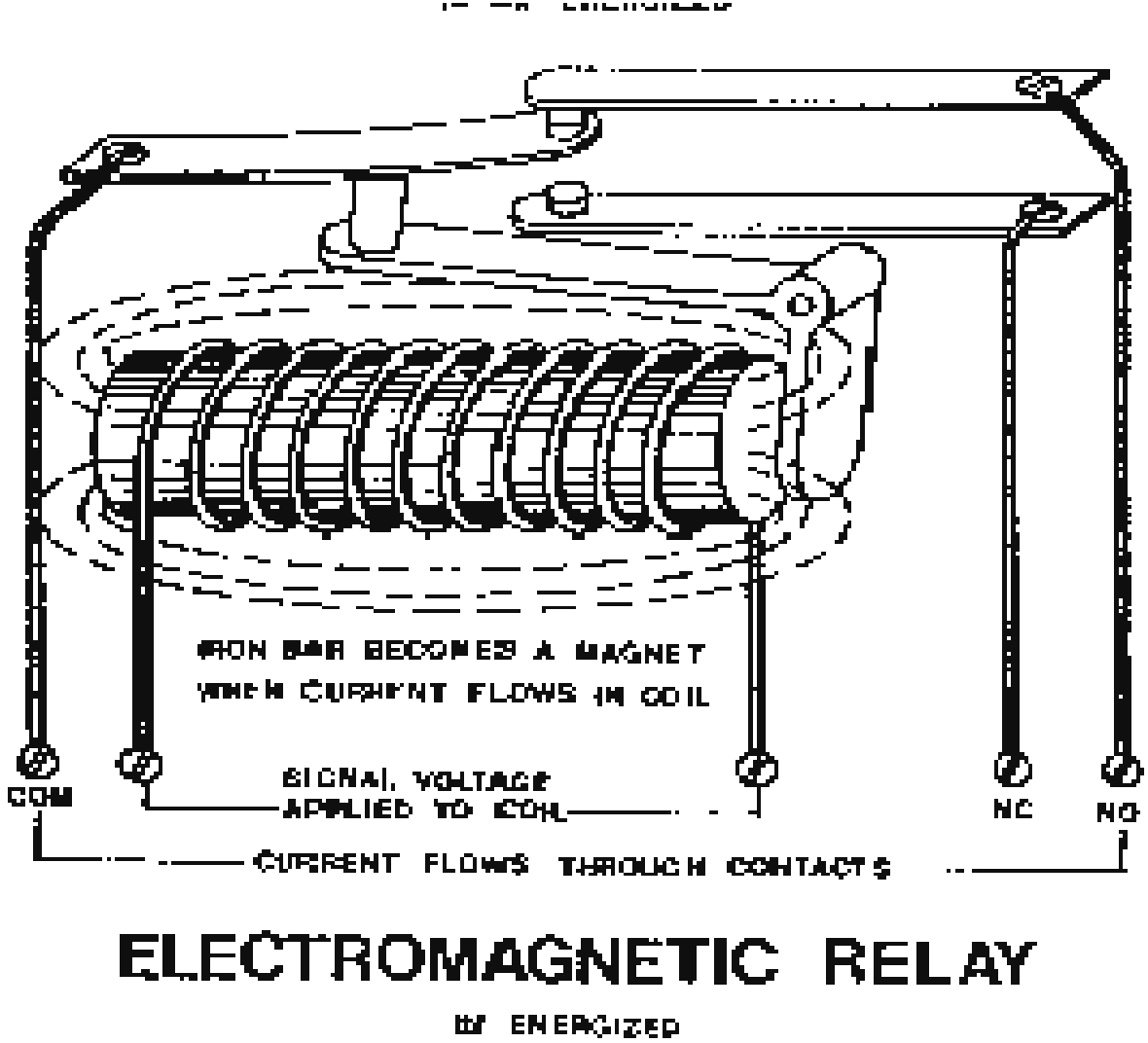
- Electromagnetic switch
- used in telephone switching systems, elevators, automobiles, etc.



ELECTROMAGNETIC RELAY

(a) DE-ENERGIZED

Relay(from Ceruzzi)



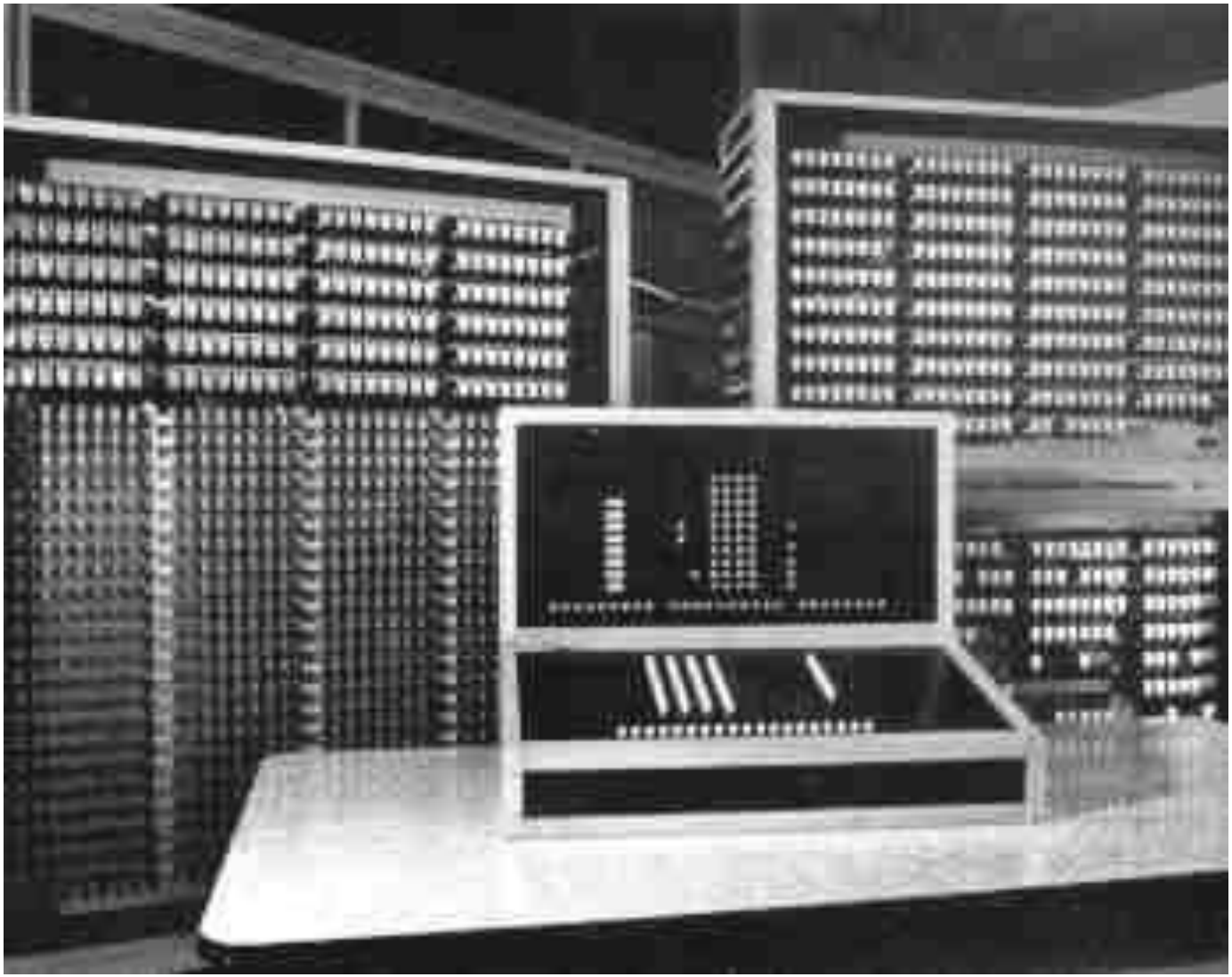
Z3 Architecture

- **Number system** **pure binary, floating point**
- **Word length** **22 bits**: sign 1 bit
- exponent 7 bits
- mantissa 14 bits
- **Memory capacity** **64 words, random access**
- Input/Output keyboard; lighted display
- **Clock** **variable, about 4-5 cycles/sec**

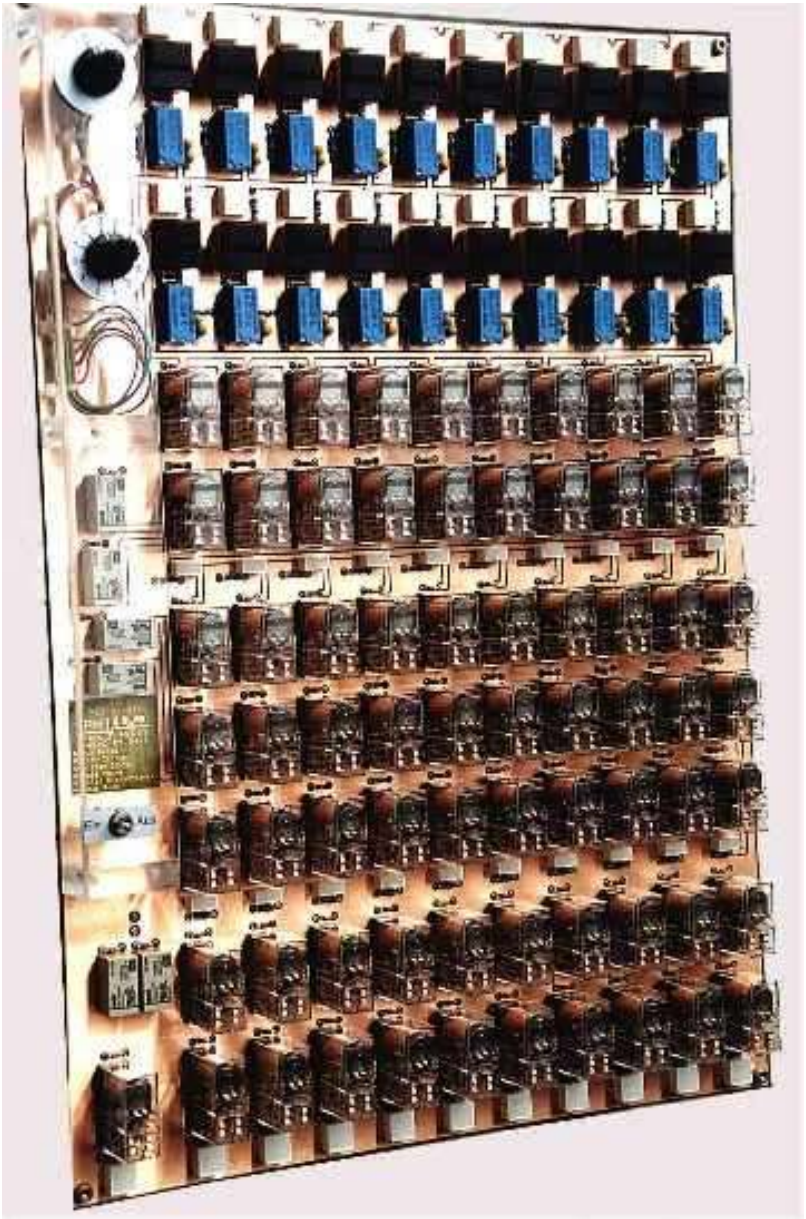
Z3 History

- **Years of operation 1941-1944**
  - destroyed in bombing raid
  - reconstructed 1961-1963 (from original plans)
- Cost $6,500 (25,000 RM)
- **Speed 3 or 4 additions per second**
  3-5 seconds per multiplication
- **Programming** **8-channel perf. filmstrip;**
  basic commands of +, -, X

Reconstruction 1960



Addierwerk dur Z3



Die Rechenmaschine Z3 von Konrad Zuse

Das Addierwerk

Grundschaltbild der Z3 mit den vier Komponenten Eingabe (E), Werkwerk (W), Speicherwerk (Sp) und Datenbusnetz (Bu)

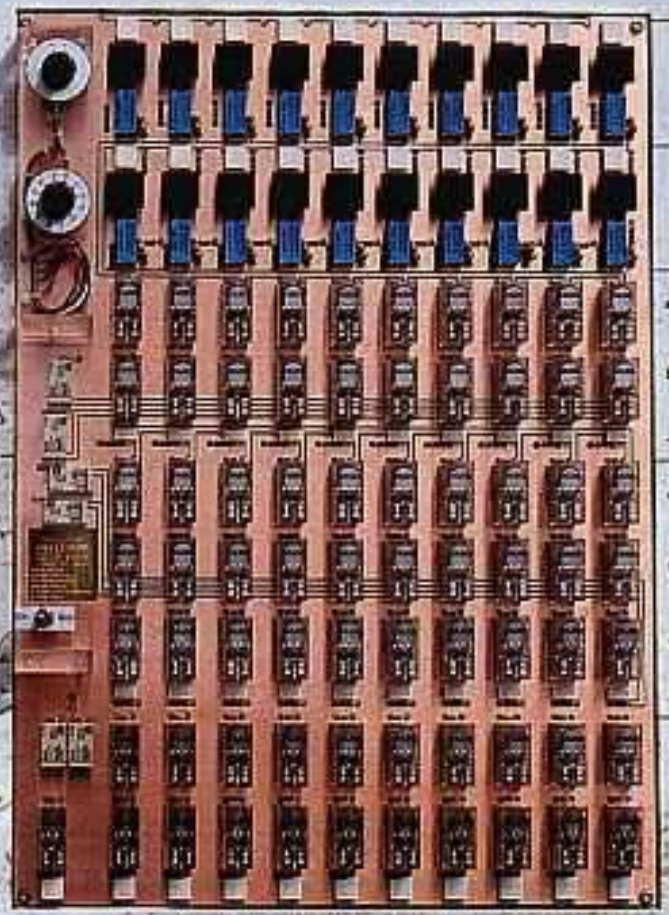
Ursprünglich für Addition / Subtraktion

Datenschalter für die Eingabe (E) und die Schritte (), 2, 3) der Addition und Subtraktion

Die Rechenmaschine Z3
Foto: Deutsches Museum München

Die Rechenmaschine Z3 wurde von Konrad Zuse in den Jahren 1938 bis 1941 gebaut. Auf dem Bild ist links die Ein- und Ausgabekonsole sowie der Lochstreifenleser zu sehen. Der Rahmen hinter der Konsole enthält die Relais für den Arbeitsspeicher. Die 22 Worte. Der Rahmen rechts enthält den Prozessor und die Steuerungseinheit für die programmierten Operationen. Die Maschine arbeitet mit Gleitkommazahlen.

Die Z3 wurde in den Anfangen Jahren ausgemustert. Der Nachbau steht heute im Deutschen Museum in München.



Register A
Das Register A hält den ersten Operanden in der binären Zweierkomplement-Darstellung. Die Schaltung verwendet Selbsthaltekontakte. Mit drei Tasten können die abgelegten Bits gelöscht und manipuliert werden.

Register B
Das Register B hält den zweiten Operanden in der binären Zweierkomplement-Darstellung. Auch hier werden Selbsthalte-Relais eingesetzt.

Schritt 1
In dieser Schaltung wird zuerst die bitweise logische XOR-Verknüpfung der Registerinhalte A und B durchgeführt, d. h. $S_i = A_i \oplus B_i$.
Das Ergebnis wird durch Leuchtdioden angezeigt und auf die S-Relais übertragen.

Schritt 2
In dieser Schaltung wird zuerst die bitweise logische AND-Verknüpfung der Registerinhalte A und B durchgeführt (Übertragsbildung).
Die i. Schalter (a_i, b_i) dienen als Übertragsbits zu dem nächsthöheren Paarbereich.

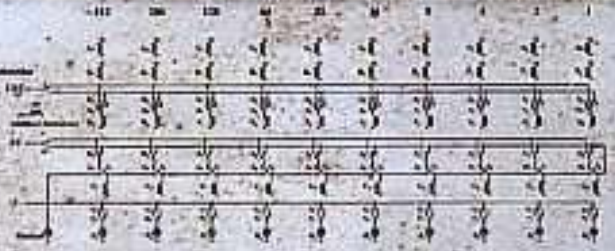
Schritt 3
In dieser Schaltung werden schließlich die Ergebnisse von den ersten beiden Schritten kombiniert. Zuletzt wird eine bitweise logische XOR-Verknüpfung der Relaisreihen S und Ü durchgeführt.

Resultat
Das Leuchtfeld am unteren Rand zeigt das Resultat der Addition an.

Die Programmsteuerung der Z3
Mit Hilfe eines Lochstreifens, der Z1 wurden Kyz Z3 am 35 mm Filmstreifen, für Programmsteuerung verwendet. Die Befehle waren voll- nicht Bits kodiert und sequentiell von dem Lochstreifen gelesen.

Die Z3 konnte folgende Befehle mit Gleitkommazahlen ausführen:
- Addition
- Subtraktion
- Multiplikation
- Division
- Quadratwurzelziehen
- Lesen von der Tastatur (Zwischenergebnis)
- Ergebnis anzeigen (Zwischenausgabe)
- Lesen aus dem Speicher
- Schreiben in den Speicher

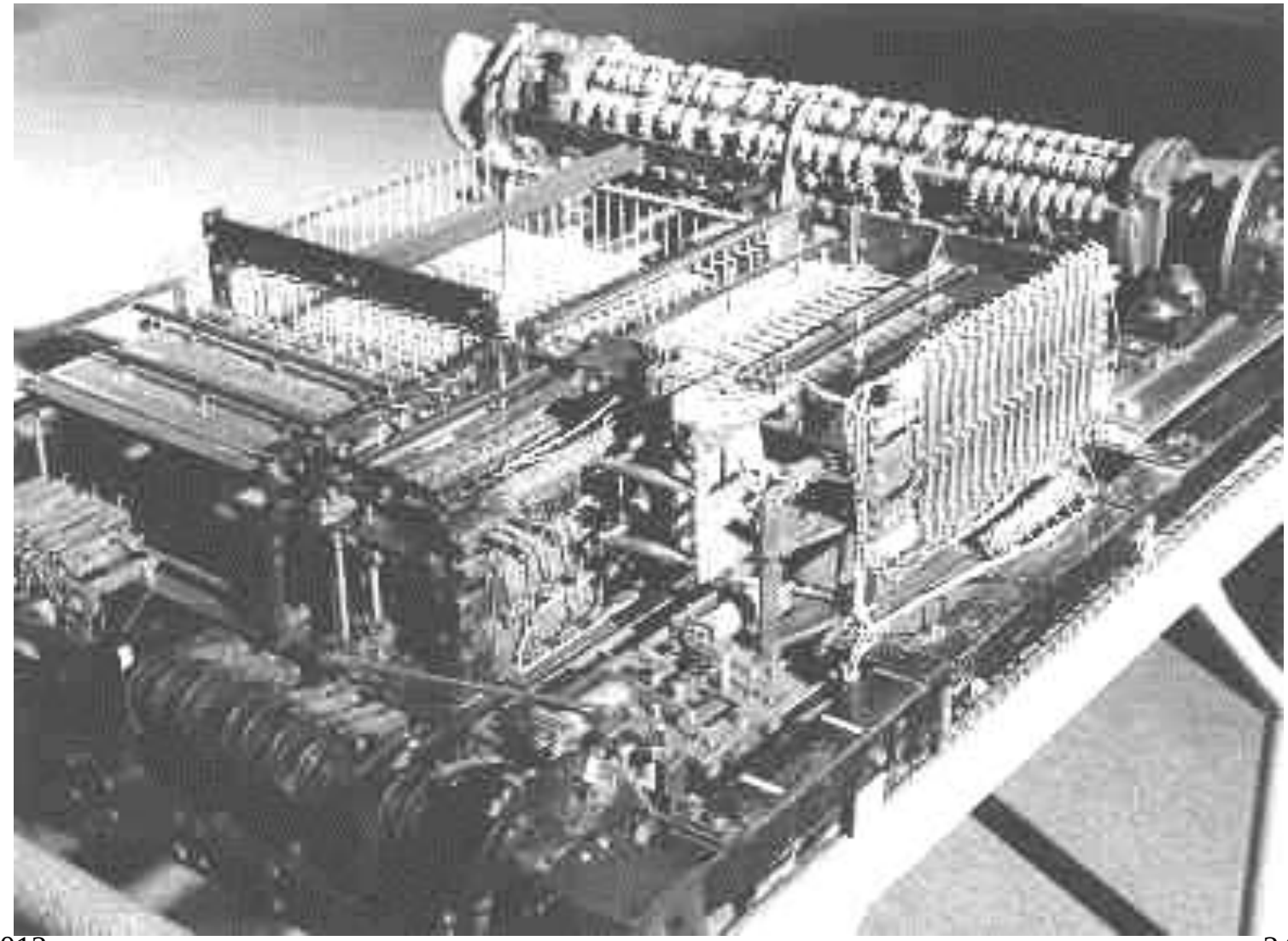
Die Lochstreifen konnten so neue Befehle verbunden werden.



Zuse's Z4

- Construction began 1942
- **Word length 32 bits**
- ***Mechanical memory 1000 words***
- In 1950, after additions, machine sent to Federal Polytechnic Institute in Zurich
- Contained a lookahead feature read three instructions ahead with 3 options for execution
- In use at ETH until 1955; FARI until 1960

Rechner du Z4



Zuse AG

A DATACOM PIONEER DIES

- *On Tuesday, January 31, 1995, George Robert Stibitz, a Bell Labs engineer who is believed to have accomplished the world's first remote computing process, died at the age of 90 at his home in Hanover, New Hampshire.*
- *In 1937, Stibitz cobbled together a primitive binary adder from dry cell batteries, metal strips from a tobacco can and flashlight bulbs in an arrangement with two telephone relays to accomplish simple arithmetic from inputs sent down a Baudot teletype circuit*

- *source: e-mail to History of Technology list, 2/11/95*

George Stibitz

- **Kitchen or K-1 Computer** **1937**

- **Complex Number Calculator** *January* **1940**
  - Samuel B. Williams, engineer
  - American Mathematical Association Meeting at Dartmouth College in Hanover, N.H. September 11, 1940

attendees sent mathematical problems to Bell Laboratories in New York via telephone lines, using a Teletype

  - attendees: John von Neumann, John Mauchly, and Norbert Weiner (among others)

Complex Number Calculator

- Technology: 450 relays, 10 crossbar switches
  - 6-8 panels (approx. 8’ x 5’ x 1’)
- Arithmetic: 8-digit precision
  - range ±0.99999999
  - binary-coded-decimal, excess three code:

• 0	0011	5	1000
• 1	0100	6	1001
• 2	0101	7	1010
• 3	0110	8	1011
• 4	0111	0	1100

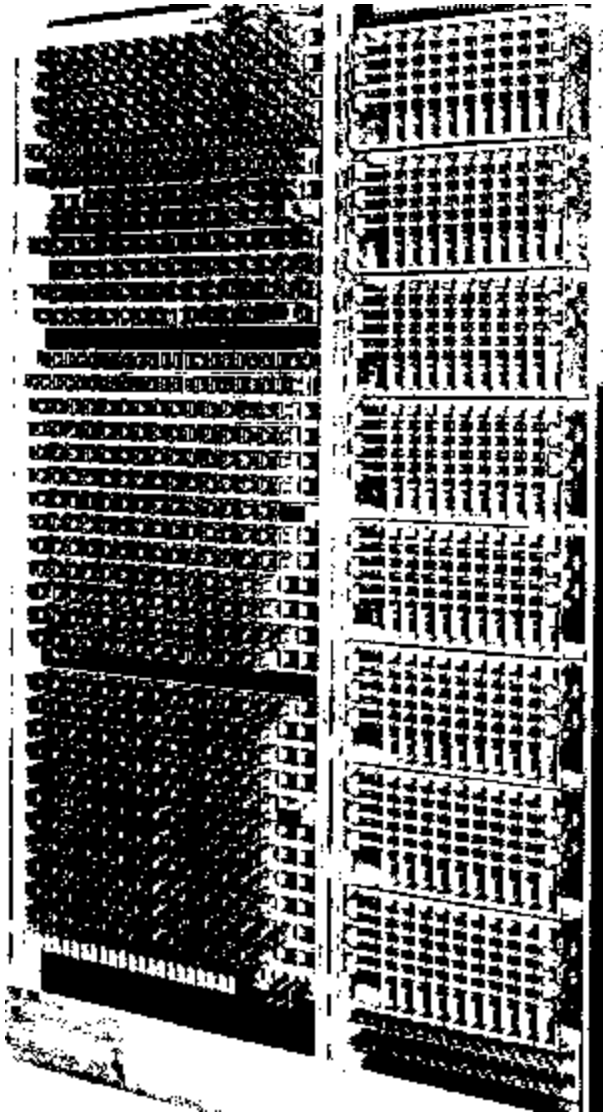
Relay Interpolator, September 1943

Decimal digit	Bi-quinary code		Binary
0	01	00001	0000
1	01	00010	0001
2	01	00100	0010
3	01	01000	0011
4	01	10000	0100
5	10	00001	0101
6	10	00010	0110
7	10	00100	0111
8	10	01000	1000
9	10	10000	1001

Bell Laboratories Machines

- Bell Labs Model III June 1944
  - **Ballistic Computer** for Army (ARL) at APG
  - ***AKA Aberdeen Machines***
- Bell Labs Model IV March 1945
  - Error Detector Mark 22 (Naval Research Labs, DC)
- Bell Labs Model V June 1946
  - **CADET** = **c**ant **a**dd, **d**oesn't **e**ven **t**ry!
  - No arithmetic circuitry; used an addition table
  - Multiplication by repeated addition
- Bell Labs Model VI **November 1950**

Bell Model III Arithmetic Unit



Characteristics

Model	**II**	**III**	**IV**	**V**
Date	1943	1944	1945	1946&7
Relays	440	1400	1425	9000+
Memory	7	10	10	30
Multiply	4 sec	1sec	1sec	0.8 sec
Cost	$20K	$65K	$65K	$500K
Panels	2	5	5	27 (**10 tons)**

Babbage's Dream come true

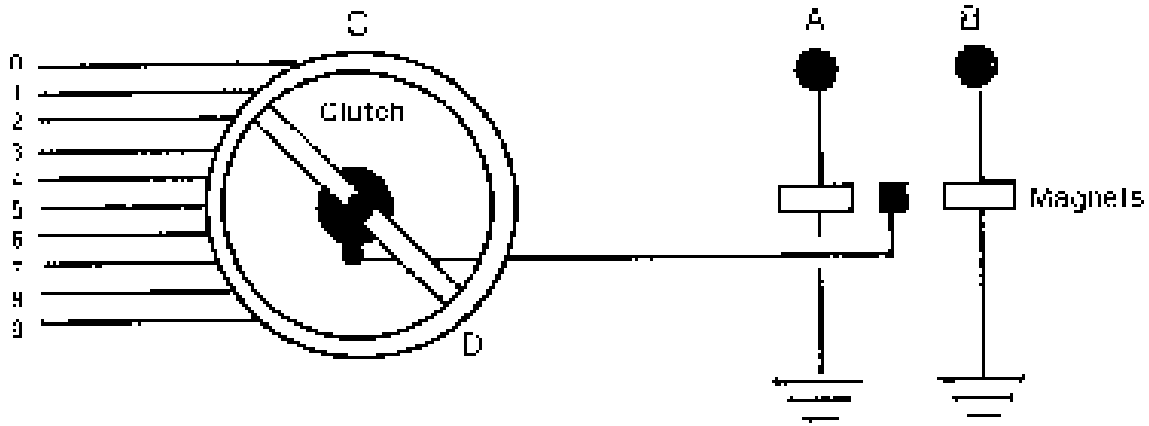
- **Howard Aiken**, Instructor, Graduate School of Engineering, Harvard University
- Influences:
  - Watson Astronomical Computing Bureau at Columbia University (EAM)
  - Babbage, *Passages in the Life of a Philosopher*
- Approached Thomas J. Watson of IBM
  - design and construction began 1939 at **IBM, in Endicott, N.Y. (as a goodwill project)**
  - B.M. Durfee, F.E. Hamilton, C.D. Lake
  - **additional funding by the U.S. Navy**

Howard Hathaway Aiken (1900-1973)

Harvard Mark I

- **IBM Automatic Sequence Controlled Calculator**
  - Operational at Harvard in May 1944
  - *Dedication: Aiken took all the credit!*
- Design: used **72** standard IBM mechanical accounting machine **registers** (each of which was a self-contained adding mechanism)
- **Control: 24-channel paper tape reader**
- Constant registers (60): manual switches
- 3 paper tape readers for tabular data, punched card for data input, electric typewriter for output

Mark I Clutch Mechanism



A: "pick-up" relay, engages wheel
B: "drop-off" relay; disengages the clutch
C: clutch and clutch arm connected to constantly rotating shaft
D: rotor arm; makes a connection with the contacts along the wheel

Figure 5.1. Sketch of a Decimal Wheel for the Mark I

Mark I Mechanical Drive

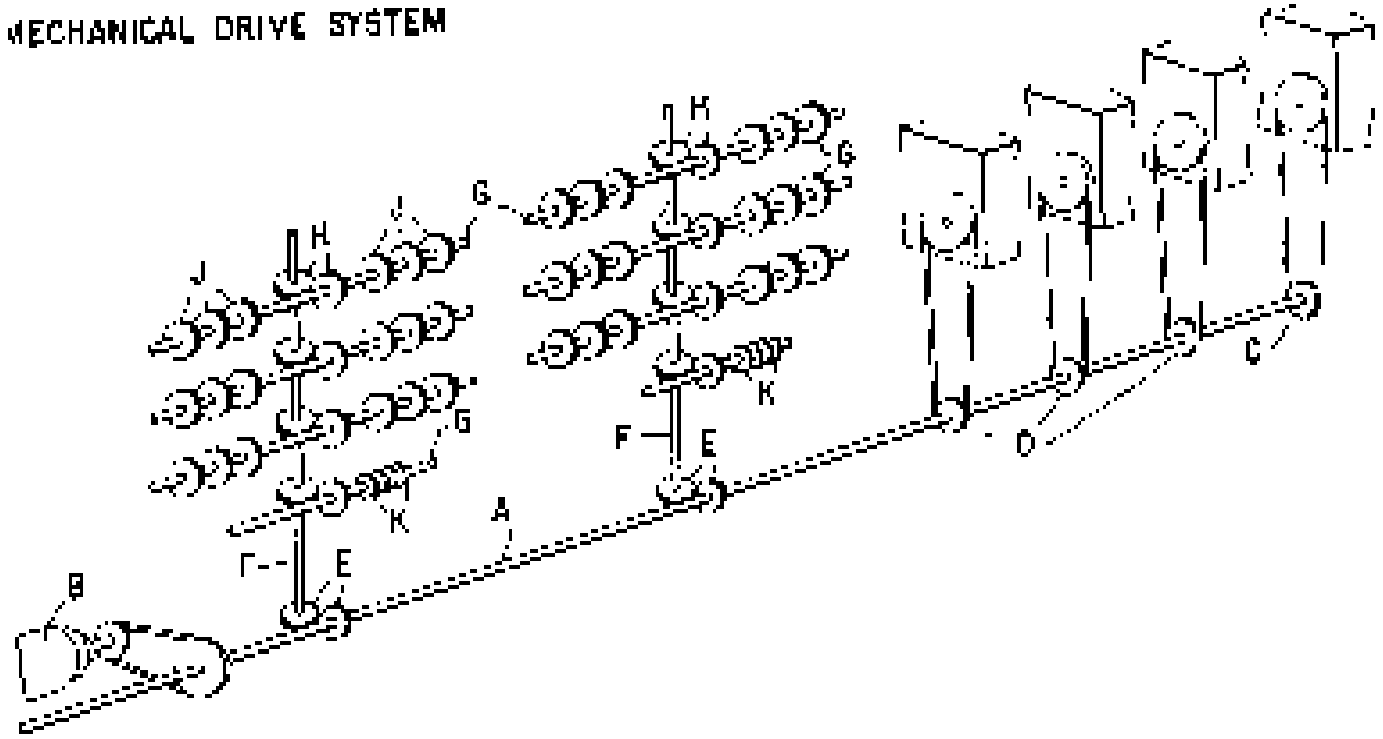
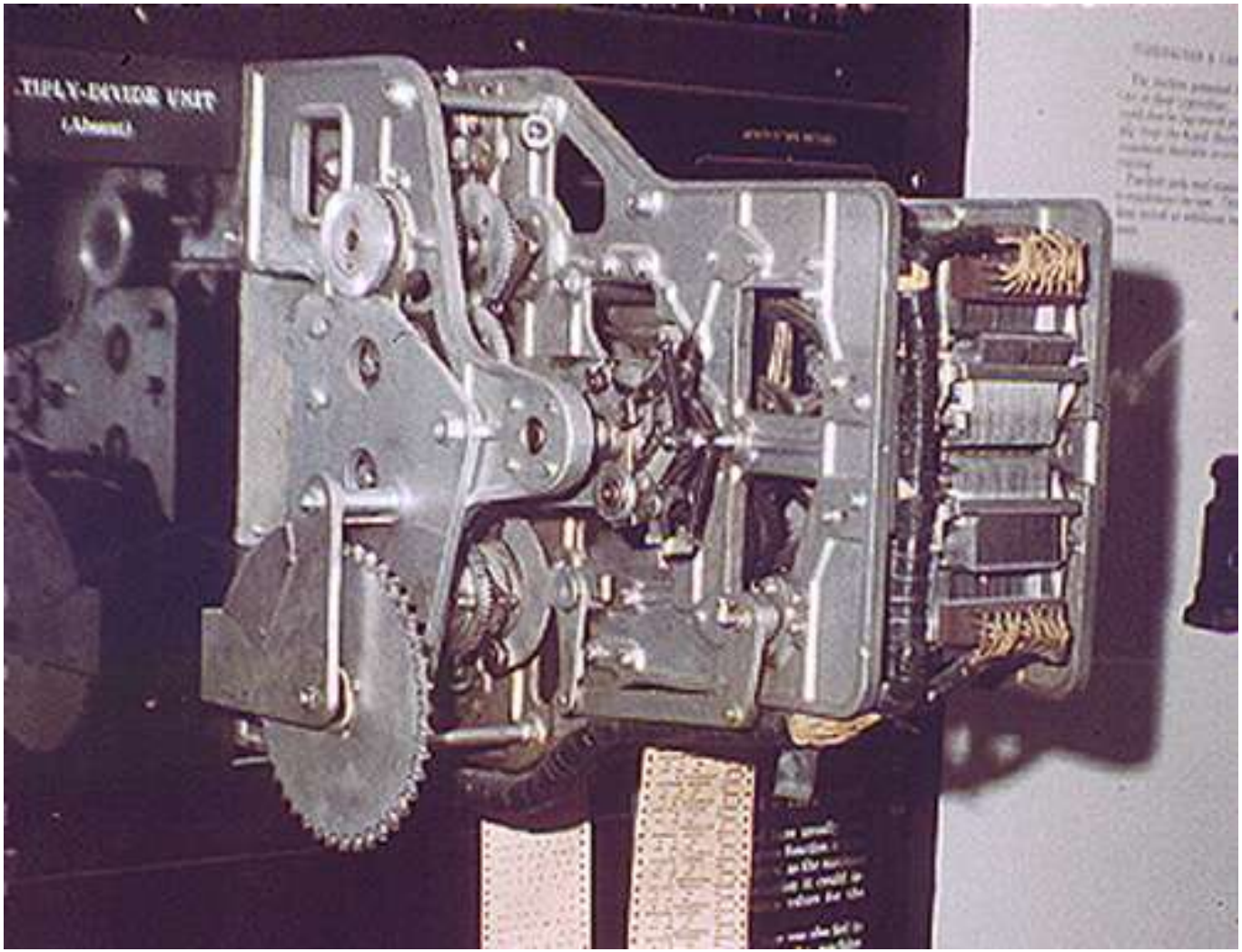


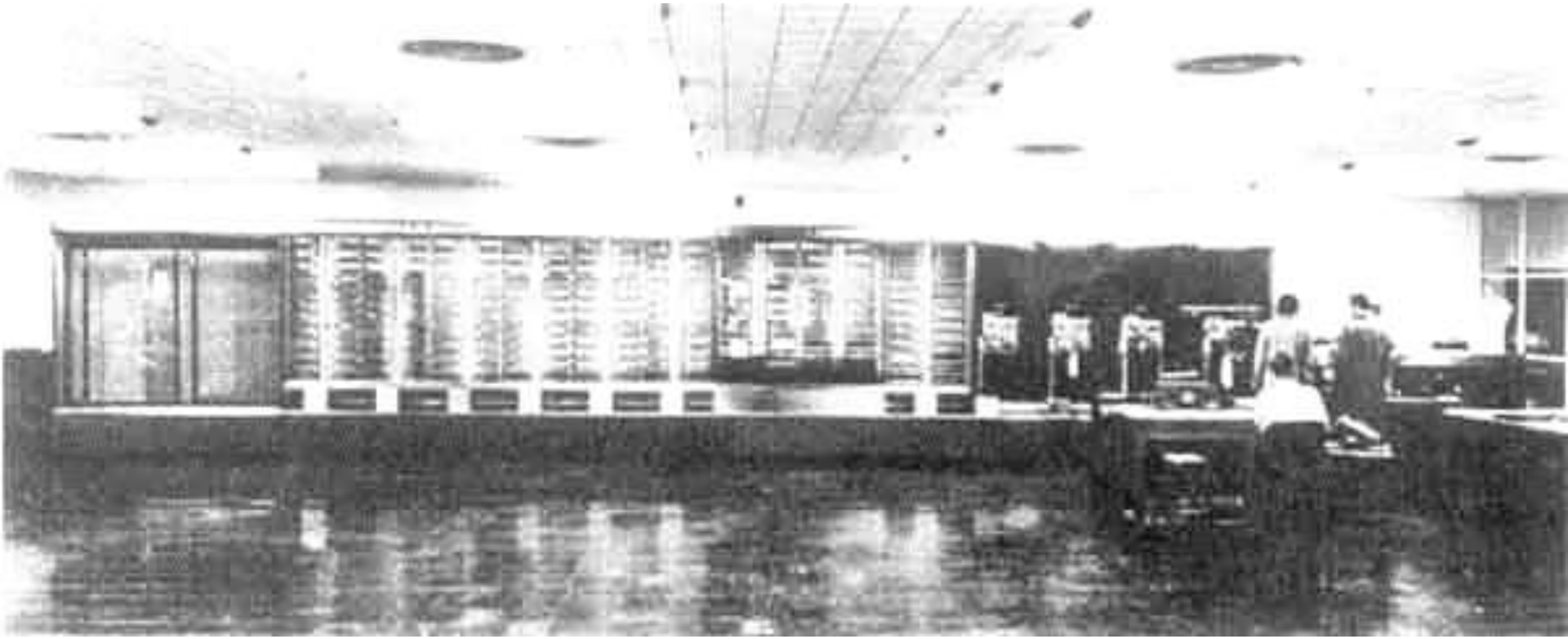
Figure 8-15. The Harvard Mark I mechanical drive system. (Photograph courtesy of the Harvard University Aiken Computation Laboratory.)

24-channel paper tape reader

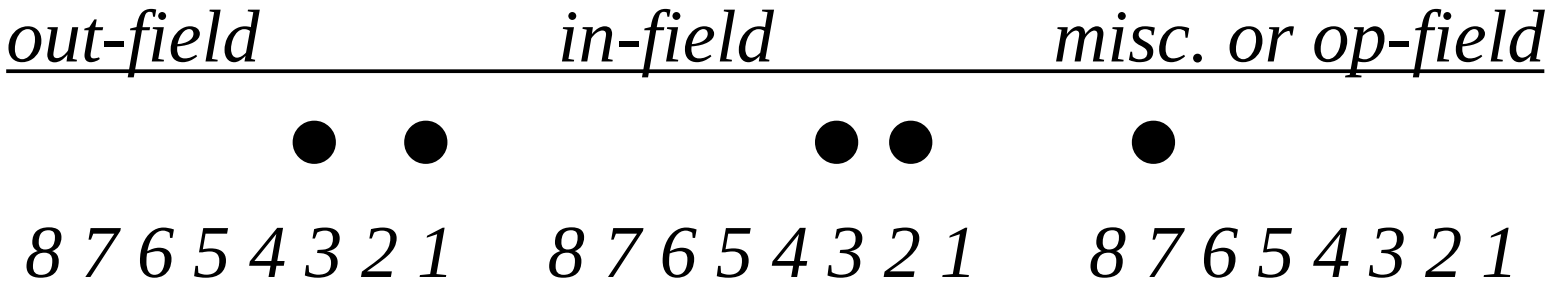
(Smithsonian photo)



- **Basic cycle time:** given the 200 rpm rotation of the main shaft, elementary operations such as adding, subtracting or clearing a register was about 0.3 seconds
- **Size: 51 feet long, 8 feet high**
- **Parts: 750,000**
  - *switches, relays, decade switches, registers (EAM)*
  - **500 miles of wire**
- **Special units**: multiplication, division, sin(*x*), 10^X, and log(*x*) [*cycle times > 60 seconds*]
  - *multiplied by partial products, a la Napier's Bones.*



- **Control: 24 channel paper tape**
  - three 8 channel groups: (two address machine):



Take the contents of Unit 5, add it to the contents of Unit 6, and go to the next instruction

- **Subsidiary Sequence Mechanism** was a large series of *plug-board panels* which allowed up to ten often used subroutines to be plug-wired into the machine

Later developments....

- **Mark II operational.....July 1947**
  - Naval Proving Ground, Dahlgren, VA
  - 13,000 specially designed electromagnetic relays
    - six pole, double throw contacts
    - latching relays
  - multiple arithmetic units
  - addition: 125 milliseconds
  - multiplication: 750 ms

- **Mark III** **Sept 1949**
  - **Naval Proving Ground, Dahlgren, VA March 1950**
- **Internally stored program**
  - 8 magnetic drums for data; used ***paging***
  - 1 magnetic drum for (4000) instructions
  - internal storage for 4,350 16-bit numbers
  - ***address modification***
  - ***indirect addressing*** of instructions

- **Mark IV** **1952**
  - **ferrite magnetic cores** to construct 200 registers
  - **United States Air Force**

Legacy

- **Lt. Grace Murray Hopper, USN**
  - **third programmer on the Mark I**
  - active in **COBOL** and early language developments

  Rear Admiral Grace Brewster Murray Hopper, first lady of software and first mother-teacher of all computer programmers, died in her sleep in her Arlington , VA. Home on January 1, 1992. She was 85.
    - J.A.N. Lee, *Computer Pioneers*, MIT Press, p.382
  - **Herbert R.J. Grosch (oldest living programmer)**
- *After Mark IV, Aiken retired from designing computers and concentrated on training the **second generation** of computer scientists (many of whom made significant contributions to the mini-computer industry around Boston's Route 123 in the 1960s and 1970s)*

Grace Murray Hopper (1906-1992)

9-2

9/9

0800 Arctan started { 1.2700 9.037 847 025
1000 " stopped - arctan ✓ 9.037 846 995 correct
13 Vc (034) MP - MC ~~2.130476415 (-3)~~ 4.615 925 059 (-2)
(033) PRO 2 2.130476415
correct 2.130676415
Relays 6-2 in 033 failed special speed test
in Relay " 11.00 test.
Relays changed
1100 Started Cosine Tape (Sine check)
1525 Started Multy Adder Test.

1545 
Relay #70 Panel F
(moth) in relay.

First actual case of bug being found.

1530 Arctangent started.
1700 closed down.

IBM Punched Card Advances

- 601 Multiplying Punch 1935
- 604 Multiplying Punch 1948
  - 1400 electronic tubes
  - 8 internal registers used in pairs (8 decimal digits)
  - 2 large plugboard panels
  - read a card, perform up to 60 different arithmetic steps and punch the output by the time the card reached the punching station (in about 80 milliseconds)
  - 5000 sold by 1958

IBM Calculators

- ***Automatic Sequence Controlled Calculator 1944***
  - *aka Harvard Mark I (May 1944)*
- **Pluggable Sequence Relay Calculator 1944-45**
  - *Aberdeen Proving Ground, Aberdeen, MD*
  - *Naval Proving Ground, Dahlgren, VA*
  - *T.J.Watson Scientific Computing Laboratory, Columbia University*
- **Card Programmed Calculator (CPC) 1948**
  - *Northrup Aviation: 604 mult. punch & 407 tabulator*
  - *700 sold*

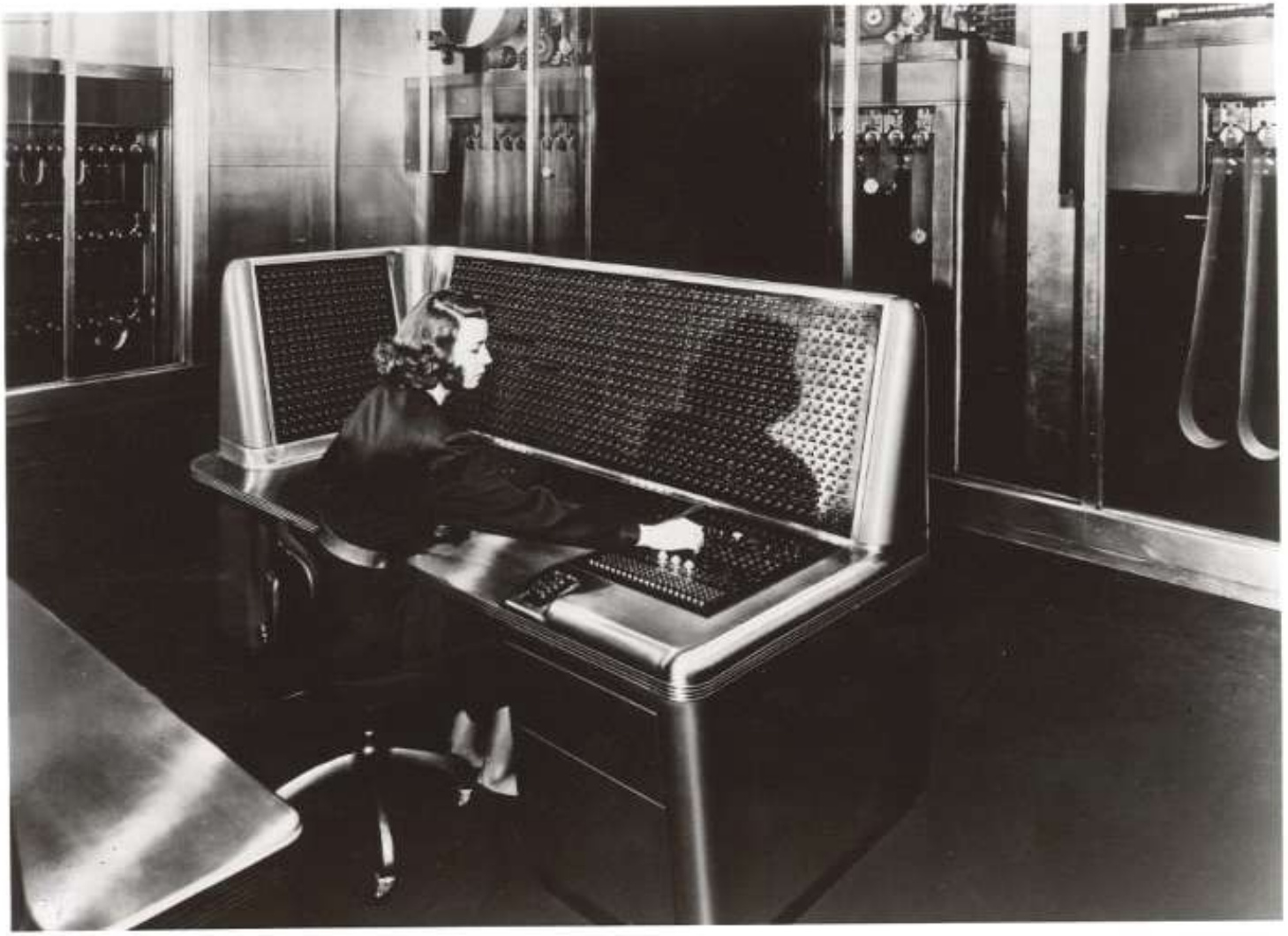
Automatic Sequence Controlled Calculator 1944 (IBM photo)

Automatic Sequence Controlled Calculator 1944 (IBM photo)

Selective Sequence Electronic Calculator (January 1948)

- 13,000 **vacuum tubes** in arithmetic unit and 8 high-speed registers (**binary coded decimal: 8:4:2:1**)
  - addition: 0.004 seconds
- 23,000 **relays** in the control structure and 150 slower-speed registers
- instructions via paper tape (66 paper tape readers)
- 1st machine used in a **service bureau**

Selective Sequence Electronic Calculator (IBM Photo)



Selective Sequence Electronic Calculator (IBM Photo)

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  - http://irb.cs.tu-berlin.de/~zuse/Konrad_Zuse

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- I. Bernard Cohen, *Howard Aiken: Portrait of a Computer Pioneer*, MIT Press, 1999
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- Herbert R. J. Grosch, *Computer: Bit Slices From a Life*, Third Millennium Books, 1991

Show and Tell

- K-1 Computer model: *Raymon Richardson*
- Letter and diagrams from Zuse's son
- Stibitz and Laravee, *Mathematics and Computers*, McGraw-Hill, 1957
- IBM, *SSEC brochure*
- IBM drum memory and read head
- Ferrite Magnetic cores
- IBM CPC plugboard
- ERA, *High Speed Computing Devices*, 1950