Alan Turing – Computer Designer

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Turing, the theoretician

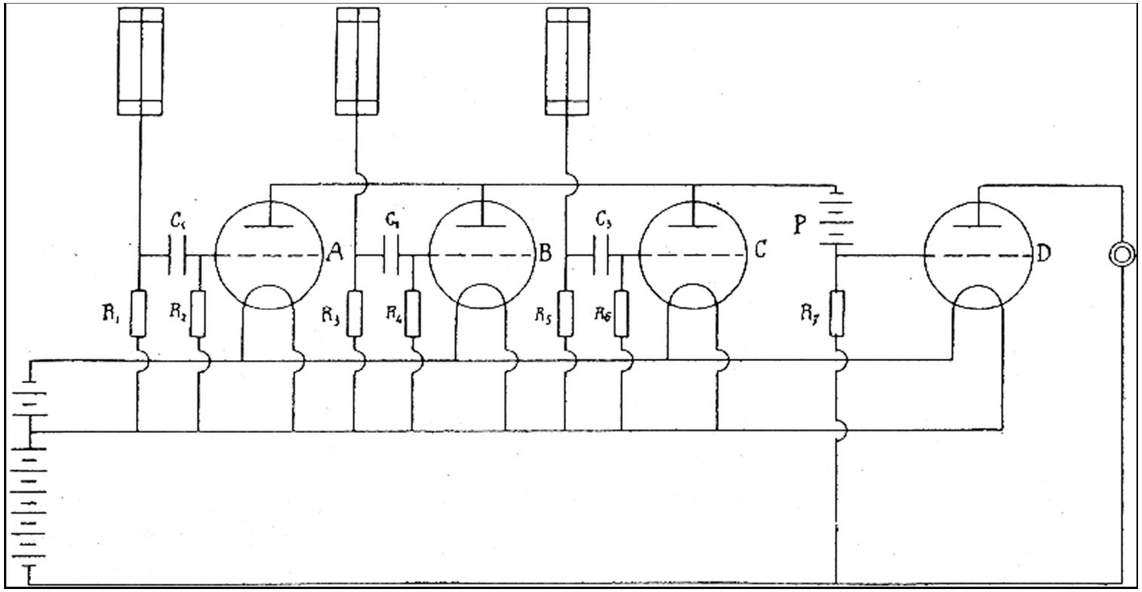
- Turing is widely regarded as a pure mathematician. After all, he was a B-star Wrangler (in the same year as Maurice Wilkes)
- "It is possible to invent a single machine which can be used to compute any computable sequence. If this machine U is supplied with the tape on the beginning of which is written the string of quintuples separated by semicolons of some computing machine M, then U will compute the same sequence as M." *(1937)*
- So how was he able to write *Proposals for development in the Mathematics Division of an Automatic Computing Engine (ACE)* by the end of 1945?

Let’s read that carefully

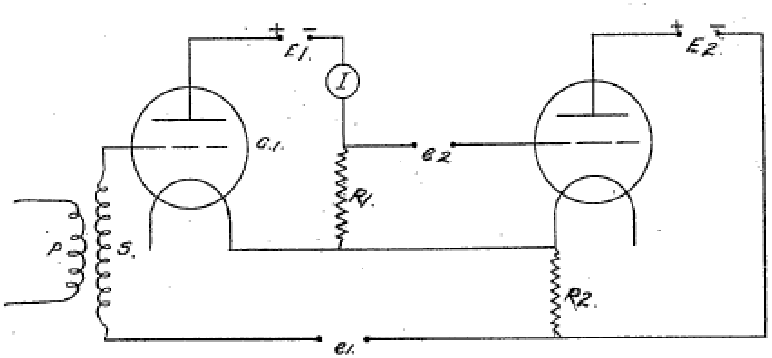
- “It is possible to invent a single machine which can be used to compute any computable sequence. If this machine U is supplied with the tape on the beginning of which is written the string of quintuples separated by semicolons of some computing machine M, then U will compute the same sequence as M.”
- The founding statement of computability theory was written in entirely physical terms.

What would it take?

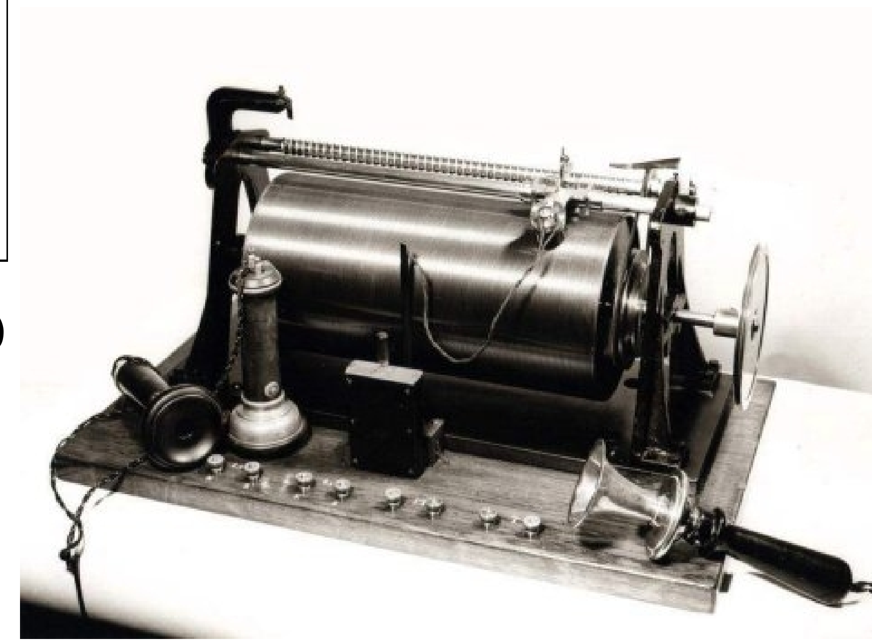
- A tape on which you can write, read and erase symbols.
  - Poulsen demonstrated magnetic wire recording in 1898.
- A way of storing symbols and performing simple logic.
  - Eccles & Jordan patented the multivibrator trigger circuit (flip-flop) in 1919.
  - Rossi invented the coincidence circuit (AND gate) in 1930.
- Building U in 1937 would have been only slightly more bizarre than building a differential analyser with Meccano.



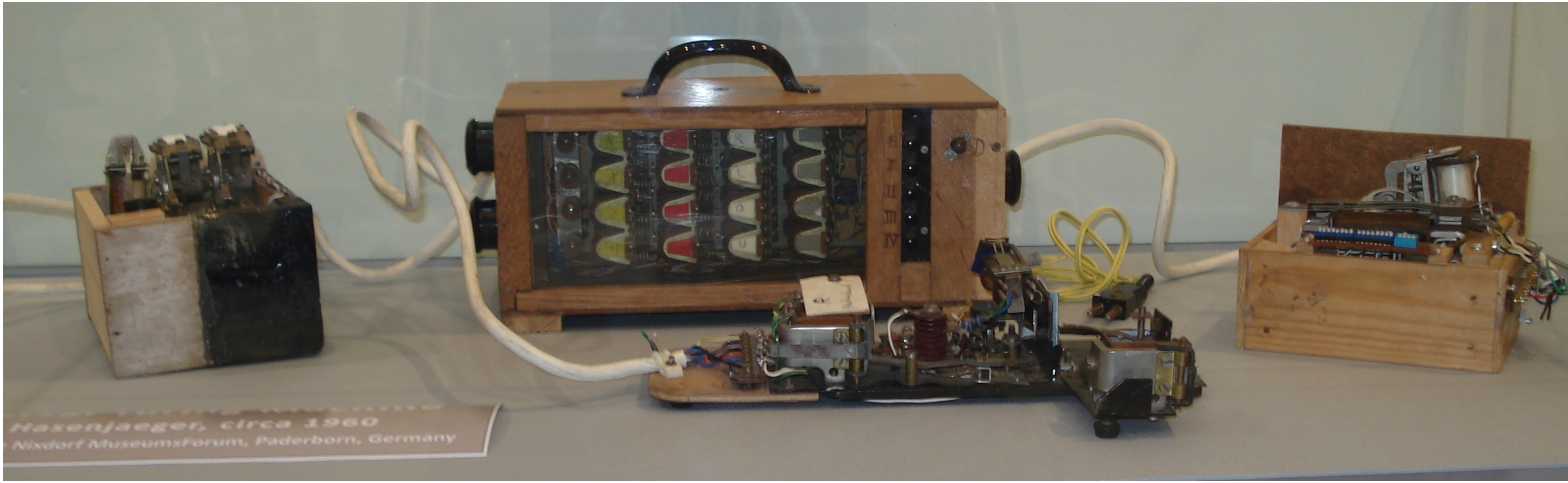
The Rossi circuit (L.Bonolis, Am.J.Phys. **79** 1133-1150, 2011)



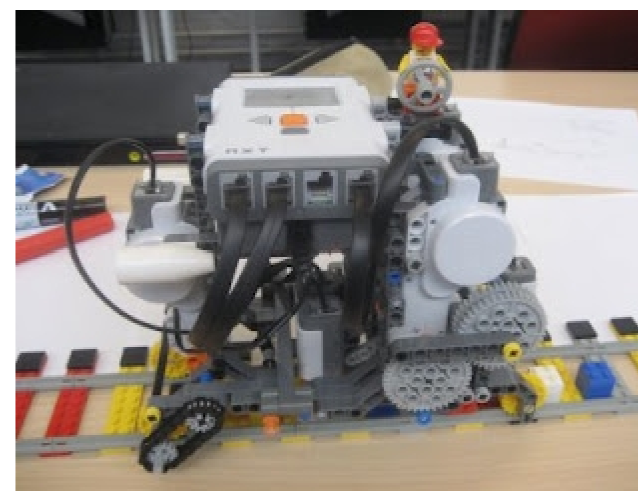
The Eccles-Jordan circuit (British patent 148582)



Poulsen “Telegraphone” wire recorder
(image from www.johansoldradios.se)



Gisbert Hasenjaeger machine (~1960)



Mike Davey machine (2010)

Lego of Doom (2009)

Turing, the pragmatist

- In 1937, he suggested adapting an analogue tide prediction machine to search for zeroes of the Riemann zeta-function.
  - By mid-1939 he'd applied for a £40 grant to build it, and his room was reported to be cluttered with high-precision gear wheels.
  - Of course he was well aware of Babbage's failed efforts.
- Also in 1937, he designed and partly constructed an electric multiplier.
- In 1940, he decided to protect his assets against a possible invasion by burying two silver ingots.
  - Unfortunately, he could never find them again.

(photo: Wikipedia)

We all know where this is, surely.

So where is this?

(photo: www.mkheritage.co.uk/hdhs)

Turing, the electronics engineer (of sorts)

- From late 1943, Turing moved from a central role at Bletchley Park to Hanslope Park, a secret radio establishment not far away. His work there, on a speech encryption device, was done with one assistant and a few square feet of bench space.
  - For about two years, he gained practical experience, filling the role of an amateur electronics engineer, and wielding his own soldering iron.

Turing, the management consultant

- At Bletchley Park, Turing saw what was needed to manage a data-intensive operation.
  - "One of our difficulties will be the maintenance of an appropriate discipline, so that we do not lose track of what we are doing. We shall need a number of efficient librarian types to keep us in order... I have already mentioned that ACE will do the work of about 10,000 [human] computers." (Turing, 1947)
- He also foresaw what systems programmers would be like, with their mystique and gibberish.

Turing on gibberish (1947)

"The masters [programmers] are liable to get replaced because as soon as any technique becomes at all stereotyped it becomes possible to devise a system of instruction tables which will enable the electronic computer to do it for itself. It may happen however that the masters will refuse to do this. They may be unwilling to let their jobs be stolen from them in this way. In that case they would surround the whole of their work with mystery and make excuses, couched in well chosen gibberish, whenever any dangerous suggestions were made."

Stirrings at the National Physical Laboratory

- The NPL Mathematics Division was approved in late 1944
  - Supported by the Ministry of Supply, Cdr Edward Travis of GCCS, Hartree, and L.J.Comrie, the New Zealander who founded Scientific Computing Service Ltd. in 1938*.
  - The Division's job was to provide and coordinate national facilities for automated computation, including military applications.
- The first head of the Mathematics Division was J.R.Womersley, better known for his later work on fluid dynamics.
  - He'd read *On Computable Numbers* before the war.
  - He visited the U.S.A. in early 1945 and learnt about both ENIAC and plans for EDVAC, just before taking up the job at NPL.

*SCS Ltd. is still registered at Companies House as a private company.

Leslie Comrie, computer

Photo: in *A Computer Perspective*, 1973, credited to Mrs B Atkinson

Turing, the civil servant

- As the war neared its end, Turing was no longer playing a major role in the cryptography world.
- In June 1945, he was visited by Womersley from NPL, and was shown von Neumann’s *First Draft of a Report on the EDVAC*.
- He started work at NPL in Teddington on 1 October 1945.

Civil servants behaving creatively

- Womersley understood the potential of universal automatic computers and was willing to foster unconventional ideas.
- He created a one-man section of his Division to study the design of an Automatic Computing Engine.
- The result: by the end of 1945, Turing's *Proposals for Development in the Mathematics Division of an Automatic Computing Engine (ACE)* was finished.
- It was presented to the NPL Executive Committee in March 1946, supported by Womersley and Hartree.
- The ACE project was approved by the committee (chaired by NPL Director Sir Charles Darwin, grandson of *the* Charles Darwin).

Out of confusion...

- In 1945, the word “computer” meant a human who operated a desk calculator.
- Bomb-aiming and gun-laying computers existed in large numbers, as mechanical analogue devices.
- A handful of semi-automatic digital computing machines existed, some electronic, but they were expensive, awkward to use, and little known.
- A few people had read the EDVAC report (including Turing), but it was an incomplete design.
  - Thus Atanasoff’s, Eckert’s and Mauchly’s thinking crossed the Atlantic.
  - Zuse’s pioneering work was unknown outside Germany.

...came enlightenment

- From this confusion, Turing's 48 typed pages synthesised the concepts of
  - a stored-program universal computer
  - a floating-point subroutine library
  - artificial intelligence
  - details such as a hardware bootstrap loader
  - and much else.
- Even read 30 or 60 years later, it is a remarkable piece of work.

Contents of the ACE report (1)

PART. I.

DESCRIPTIVE ACCOUNT.

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Contents of the ACE report (2)

PART II.

TECHNICAL PROPOSALS.

Contents, transcribed

Drawings of logic elements

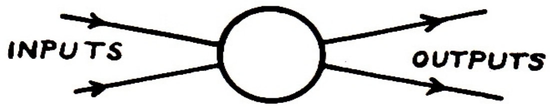


FIG. 1

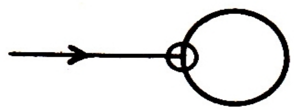
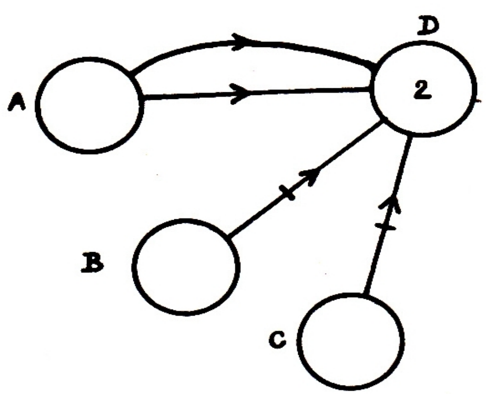


FIG. 2



Turing's notation derives from W.S.McCulloch & W.Pitts, *A Logical Calculus of the Ideas Immanent in Nervous Activity*, Bull. Math. Biophysics, 5, 115-133, 1943. They cited *On Computable Numbers*.

Drawings of logical sub-systems

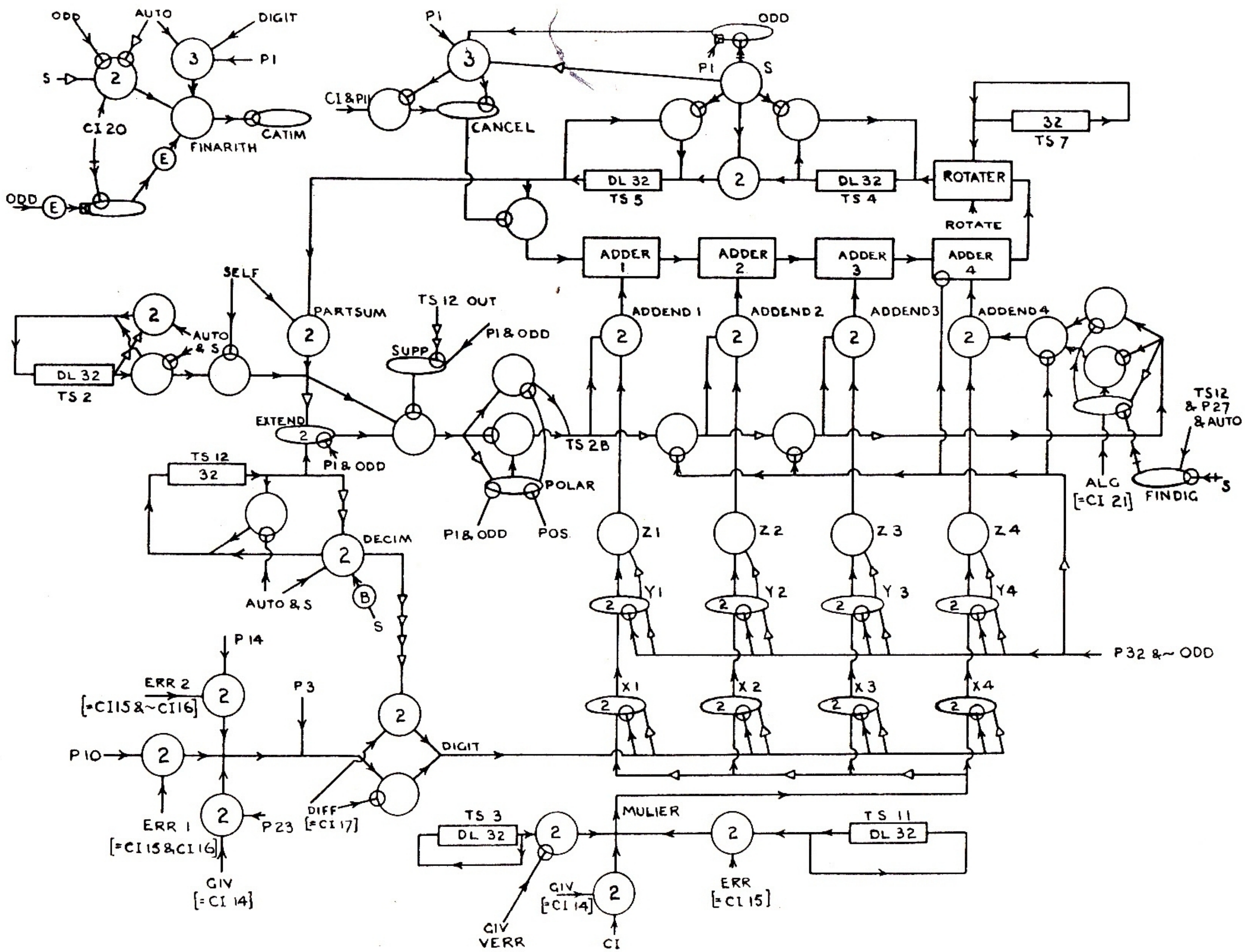


FIG 32 TRULY ARITHMETIC OPERATIONS

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Detailed electronics
for standard logic elements

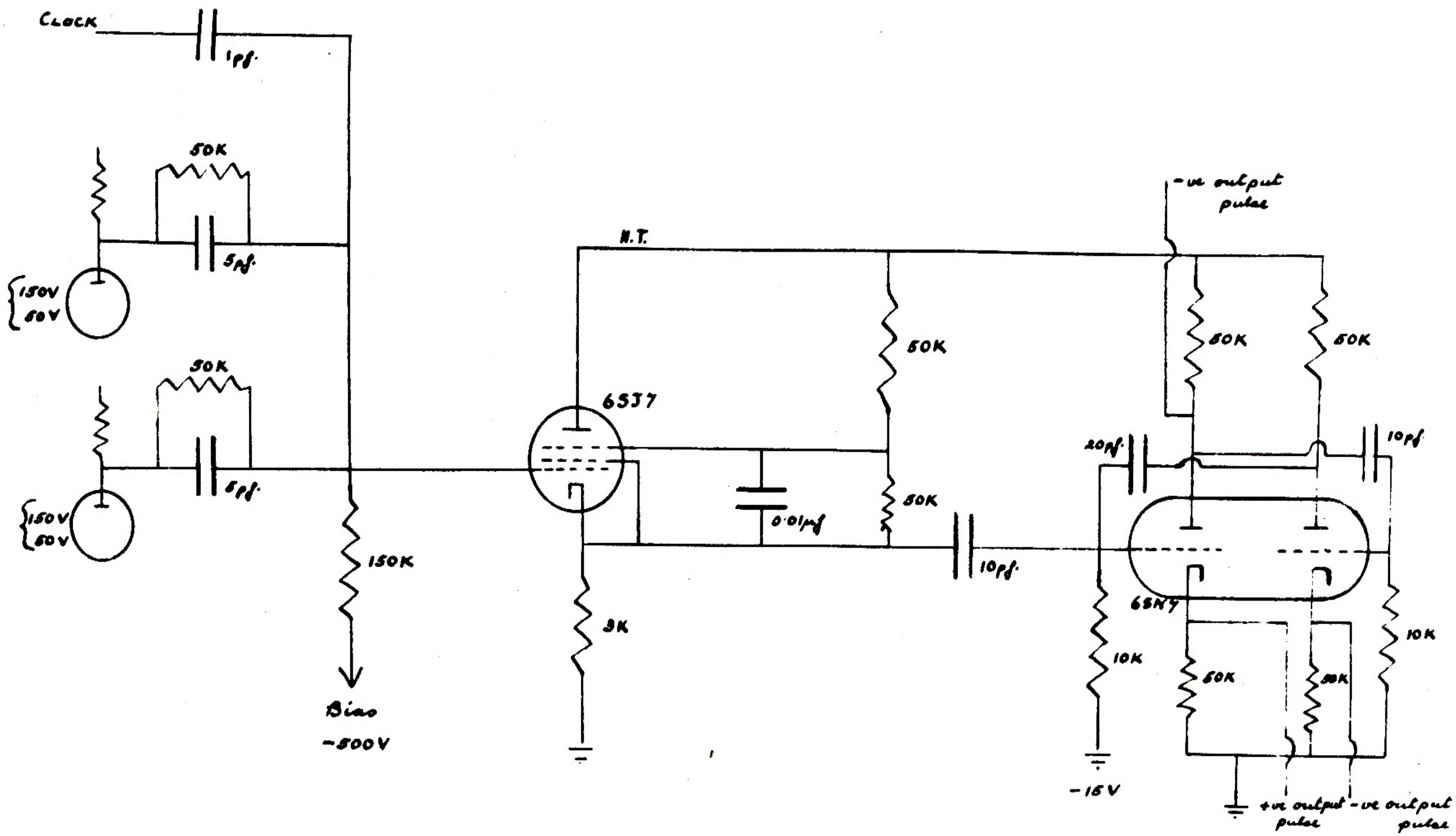

FIG. 47. "LIMITING AMPLIFIER" CIRCUIT

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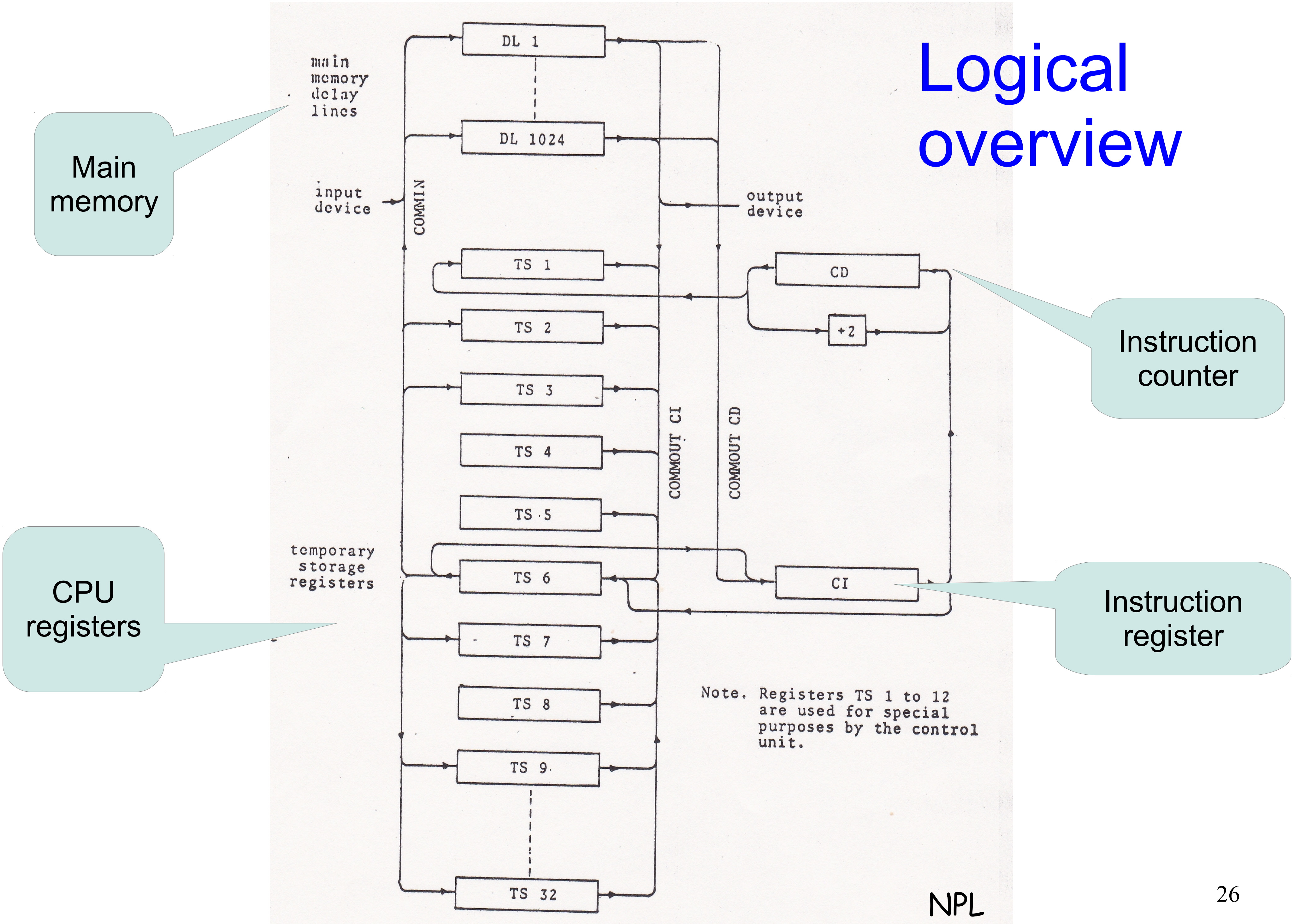
Overview

- An outline of the principles of stored program computers, binary representation, and floating point arithmetic
- A detailed architecture and instruction set
- Detailed logic diagrams, and electronic circuits for logic elements
- Example programs
- A budget estimate of £11,200 (twenty times Turing’s annual salary at NPL)

Main features of ACE CPU

- Serial 1 MHz machine with 32 bit words
  - That's about 0.03 MIPS
  - "word" in this usage appears to have been coined by Turing
- 32 registers
  - TS = temporary storage, actually a short mercury delay line
- Register-to-register instruction set
  - EDVAC was an accumulator machine
- Only 11 instructions

Logical overview



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Main features of ACE software

- Proposed applications ranged from numerical analysis (expected by NPL) to counting butchers, solving jigsaws, and chess (certainly not expected).
- Foresaw relocatable code and something very like assembly language.
- Foresaw a subroutine library, including a stack for nested subroutine calls.

Turing's basic subroutines

```
INDEXIN     TS28 ← M[TS27]

DISCRIM     TS24 ← if TS8 = 0 then TS16 else TS15

PLUSIND     TS27 ← TS27 + 1

TRANS45     TS20,21 ← TS22,23

BURY        M[TS31] ← TS1 + 1; TS31 ← TS31 + 1;
            go to M[TS1]

UNBURY      go to M[TS31 ← TS31 - 1]

MULTIP      TS22,23 ← TS 18,19 x TS20,21

ADD         TS22,23 ← TS 18,19 + TS20,21

BINDEC      Convert TS22,23 to card image in DL11
```

(As transcribed into 1970's notation by Bob Doran and me.)

Turing’s polynomial program

CALPOL.

CALPOL 1. Clear TS 22,23; DL 1,14-TS 27; DL 1,15-TS 29.
CALPOL 8.

CALPOL 8. B,BURY; B,INDEXIN; TS 28-TS 18; B,BURY;
B,PLUSIND; B,BURY; B,INDEXIN; TS 28-TS19;
B,BURY; B,ADD; B,BURY; B,PLUSIND; TS 27-TS 2;
TS 29-TS 3; AND; Q,CALPOL 40; TS 6-TS 15; Q,CALPOL 37;
TS 6-TS 16; B,BURY; B,DISCRIM; B,1.

CALPOL 37. TS 13-TS 18; TS 14-TS 19; B,BURY; B,TRANS 45;
B,BURY; B,MULTIP; B,BURY; B,TRANS 45. CALPOL 49.

CALPOL 49. B,CALPOL 8.

CALPOL 50. TS 22-TS 25; TS 23-TS 26; B,UNBURY.

For discussion, including bug fixes, see Carpenter and Doran, *The Other Turing Machine*, Computer J. **20** (1977) 269-279

Summary of formative ideas (1)

1. Binary implementation using standardised electronic logic elements*

2. Complete notation for combinational* and sequential circuits

3. Memory-Control-Arithmetic Unit-I/O architecture*

4. Stored program*

5. Conditional branch instructions (clumsy)*

6. Address mapping (interleaving)

7. Instruction address register and instruction register

* *Also found in the EDVAC report. Have not analysed list vs Colossus.*

Summary of formative ideas (2)

8. Multiple fast registers in CPU, for data and addressing; register-register instructions.

9. Microcode; hierarchical architecture

10. Whole-card I/O operations (almost DMA)

11. Complete set of arithmetic, logical and rotate orders

12. Built in error detection and margin tests

13. Floating point arithmetic

14. Hardware bootstrap loader (initial program load)

Summary of formative ideas (3)

15. Subroutine stack
16. Modular programming; subroutine library
17. Documentation standards
18. Link editor; symbolic addresses; programs treated as data
19. Run time systems (I/O conversions; hints of macro expansion)
20. Nonnumerical applications
21. Artificial intelligence

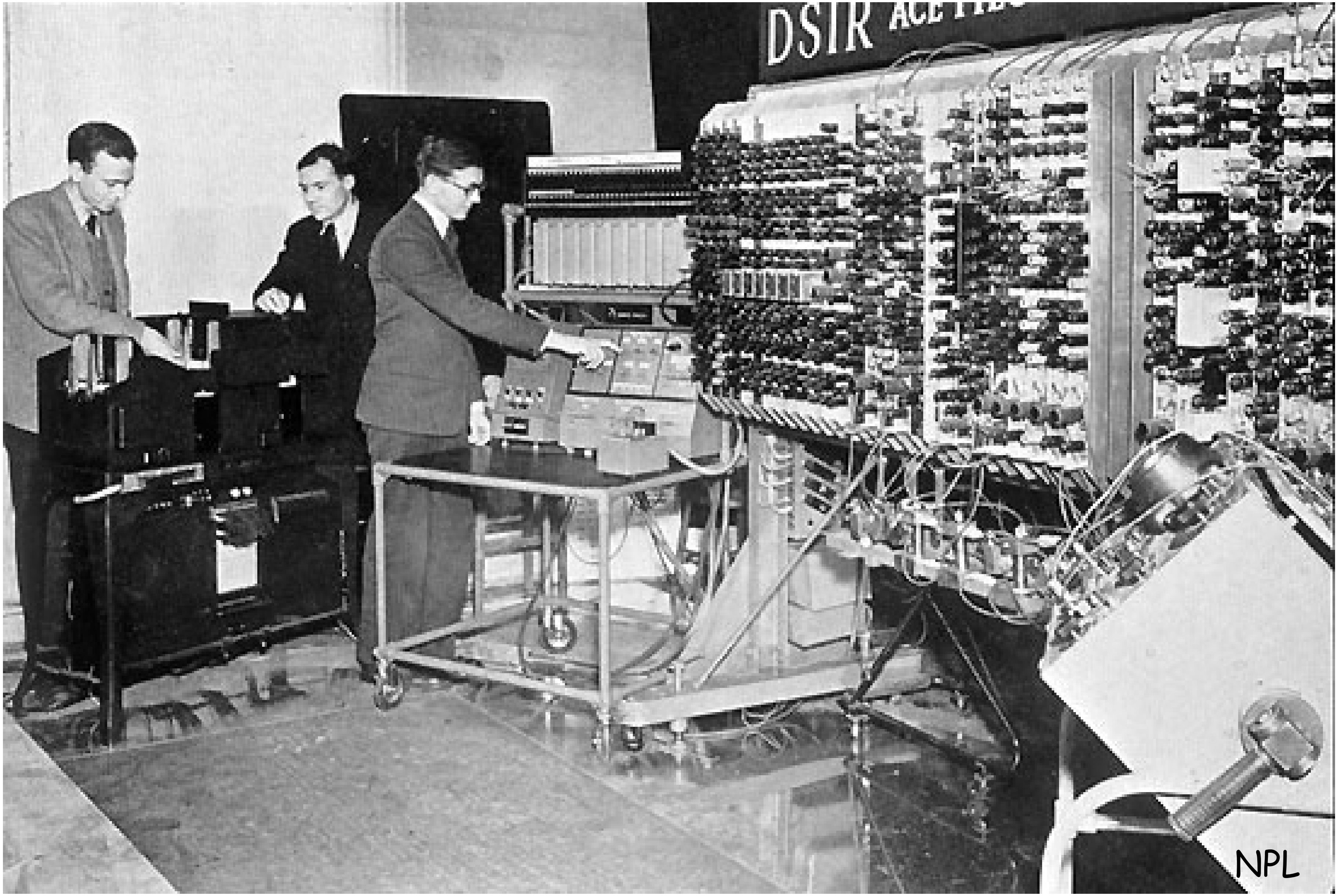
What happened to Turing's design?

- ACE went through many design cycles after the project was approved.
  - The most notorious change was the change from interleaved instructions to optimum coding, where each machine instruction includes the address of its successor.
- Turing the pragmatist was frustrated by slow progress under peacetime Civil Service conditions.
- He left NPL for Manchester, via a short return to Cambridge.

The ACE family

- Pilot ACE finally ran at NPL in May 1950.
  - The English Electric DEUCE (1955) was directly derived from Pilot ACE.
- The anachronistic full scale ACE (1958)
- The Post Office/RRDE MOSAIC (1953)
- An EMI one-off ‘business machine’ (~1956)
- The Bendix G-15 (1956)
- The Packard-Bell 250 (1960)

The Pilot ACE in 1950

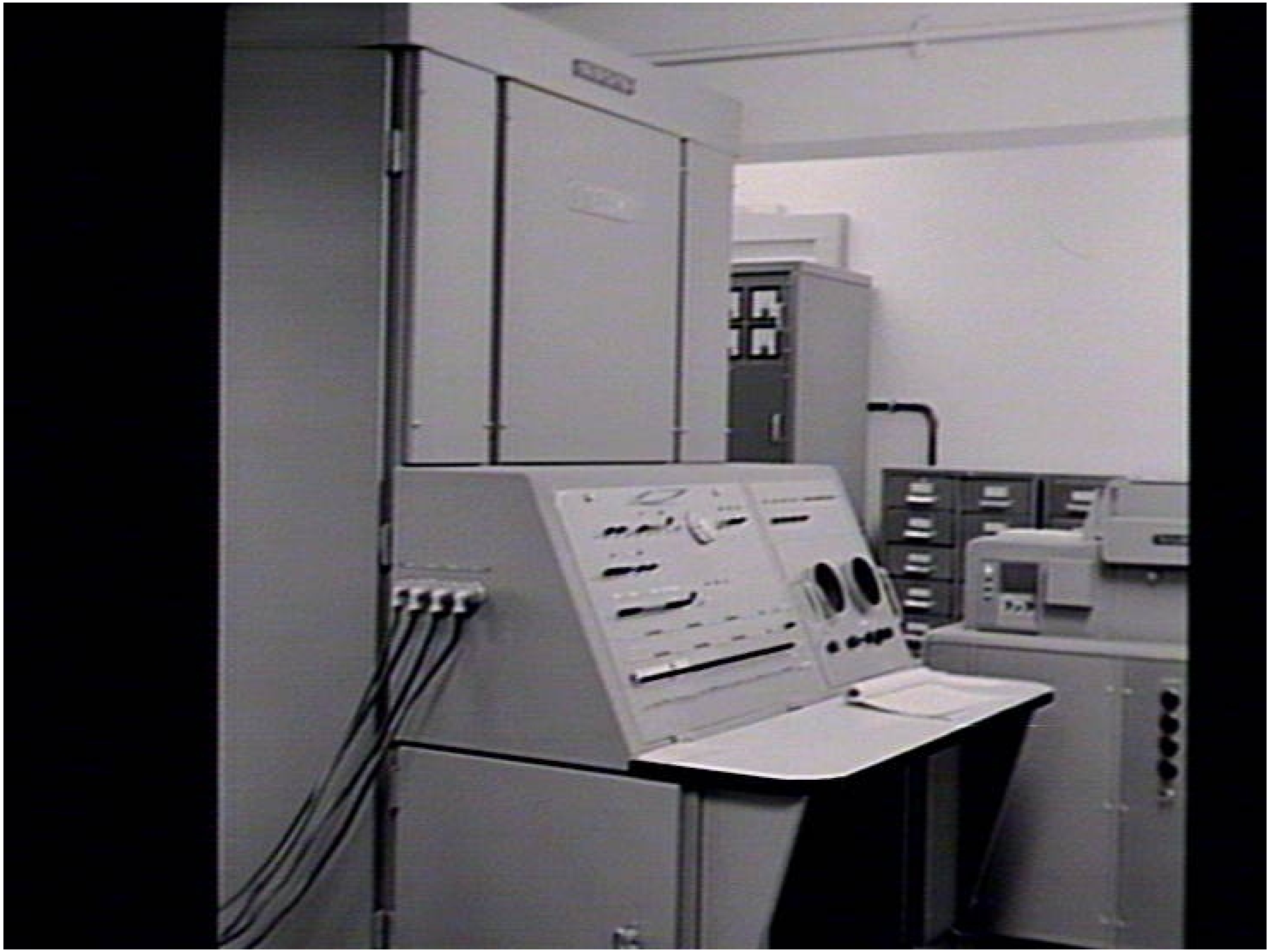


G. G. Allway, E. A. Newman and J. H. Wilkinson.

What the DEUCE?

- Gordon Bell, designer of the PDP-11, used a DEUCE as a Fulbright Scholar in Australia. The PDP-11 was the first widespread register-register machine. Bell wrote: "DEUCE certainly influenced my thinking -- some of it was negative because I was determined not to design a computer that was so difficult and tricky to program."
  - We can take that as a comment on optimum coding.
- The Unibus concept in the PDP-11 is very reminiscent of the ACE architecture, with its common input and output lines linking all the central registers and main memory together.
  - However, the Ferranti Pegasus (1956) was also very influential on the PDP-11.

The DEUCE that Gordon Bell used



This DEUCE was at the University of Technology NSW Australia
(© Mitchell Library, State Library of NSW, users.tpg.com.au/eedeuce/)

What happened to Turing’s ideas?

- All of them resurfaced; the question is how much of that was re-discovery, and how much was unacknowledged re-use.
- The 1945 ACE report, mimeographed in perhaps 50 or 100 copies, was out of stock by 1948 and vanished from view until 1972.
- The Cambridge team, especially Wilkes, never admitted to much influence by Turing.
  - Stanley Gill, however, worked on Pilot ACE and EDSAC simultaneously.
- In practice, the Manchester team also mainly followed the EDVAC line.

Where did Turing's ideas resurface? (1)

- Address mapping resurfaced in Manchester, most famously in Atlas (1962).
- The instruction counter and instruction register became universal, perhaps because there's really no other way to do it.
- Multiple fast registers in CPU, for data and addressing, became widespread in the 1960s, for example in the IBM 360.
  - The 1949 Manchester B-line, the first index register, was foreshadowed in Turing's INDEXIN routine.
  - Ferranti Pegasus (1956) had multiple registers.

Where did Turing’s ideas resurface? (2)

- Microcode; hierarchical architecture
  - presaged in MIT Whirlwind (1947)
  - reappeared most famously in Cambridge (EDSAC2, 1958).
- Whole-card I/O operations (almost DMA).
  - DMA is credited to the NBS DYSEAC (1954)
  - channel I/O is credited to the IBM 709 (1957).

Where did Turing's ideas resurface? (3)

- Complete set of arithmetic, logical and rotate orders (probably suggested by cryptanalysis requirements).
  - Logical instructions in Manchester Mark I (1949)
  - The IBM 701 had SHIFT and AND instructions (1952).
- Built in error detection and margin tests
  - Turing knew about this need from Bletchley Park experience (or from T. Flowers?)
  - Other builders of thermionic valve computers had to learn it the hard way.

Where did Turing's ideas resurface? (4)

- Floating point arithmetic (in electronics)
  - Appeared in Manchester MEG (the prototype Ferranti Mercury) and the IBM 704 (1954)
  - Known conceptually since 1914
  - Already seen in electromechanical machines (Zuse, 1938; Harvard Mark II, 1944; Stibitz Model V, 1945)
- Bootstrap loader
  - Appeared in IBM 701 (1952)

Where did Turing's ideas resurface? (5)

- Modular programming; subroutine library.
  - Reinvented by Grace Hopper (1951-2) and by Wilkes, Wheeler and Gill (1951).
- Subroutine stack
  - Appeared in Algol before 1960.
  - Appeared in hardware in English Electric KDF9 (1960), Burroughs B5000 (1961), Atlas (1962).

Where did Turing's ideas resurface? (6)

- Link editor; symbolic addresses; programs treated as data.
  - EDSAC had instruction mnemonics (1949).
  - Turing contributed to the Manchester software effort, but the first real Autocode solution was due to Tony Brooker (1954).
- Documentation standards
  - Usually credited to Grace Hopper around 1952, but Turing recognised the need 3 years before any stored program machine was built.

Where did Turing's ideas resurface? (7)

- Run time systems (I/O conversions etc.).
  - Became universal, and another remarkable Turingesque foresight in 1945.
- Nonnumerical applications
  - Presumably inspired by cryptanalysis, but Turing couldn't mention that in writing.
- Artificial intelligence
  - At least Turing got credit for this one (along with Shannon, with whom he had discussed it during the war).

How much credit should Turing get?

- It’s clear that Turing was the first to work seriously on a general-purpose computer design in the UK, in late 1945.
- The community of pioneers in the UK and the US was relatively small until 1954 when Turing died; we can assume that word of mouth had a significant effect, and that ideas were not always properly credited.
- We know that apart from NPL, there was some direct influence in Manchester but little influence in Cambridge.
- It’s impossible to tell, today, to what extent Turing’s amazing foresights were passed on indirectly to other pioneers, or to what extent they were simply rediscovered when their time came.

http://turing100.net/

Turing's 100th birthday party.

King's College, June 15-16, 2012.

NPL

Sources and further reading

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- *The other Turing machine,* B.E. Carpenter & R.W. Doran, Computer J. **20** (1977) 269-279.
- *A.M.Turing's ACE Report of 1946 and other papers*, Brian E. Carpenter and Robert W. Doran (editors), Vol. 10 in the Charles Babbage Institute Reprint Series, MIT Press, 1986.
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- *Innovating for Failure: Government Policy and the Early British Computer Industry*, John Hendry, MIT Press, 1989.
- *Alan Turing's Automatic Computing Engine*, B. Jack Copeland (ed.), Oxford, 2005.
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- *Alan Turing and his Contemporaries*, Simon Lavington (ed.), BCS, 2012.
- *A Survey and Taxonomy of I/O Systems*, Mark Smotherman, last updated July 2006, www.cs.clemson.edu/~mark/io_hist.html
- *The Manchester Computer: A Revised History (Pts 1 & 2),* B. Jack Copeland, Annals Hist. Comp. **33**(1), (2011) 4-21 & 22-37.
- Wikipedia and Google, of course.