Alan Turing
Father of the Modern Computer

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Alan Turing 1912-1954

Snapped for a passport photo[2]

Introduction

As anyone who can operate a personal computer knows, the way to make the machine perform some desired task is to open the appropriate program stored in the computer's memory. Life was not always so simple. The earliest large-scale electronic digital computers, the British **Colossus** (1944) and the American **ENIAC** (1945), did not store programs in memory. To set up these computers for a fresh task, it was necessary to modify some of the machine's wiring, re-routing cables by hand and setting switches. The basic principle of the modern computer—the idea of controlling the machine's operations by means of a program of coded instructions stored in the computer's memory—was conceived by Alan Turing.

Turing's abstract 'universal computing machine' of 1936, soon known simply as the **universal Turing machine**, consists of a limitless memory, in which both data and instructions are stored, and a scanner that moves back and forth through the **memory**, symbol by symbol, reading what it finds and writing further symbols.[2] By inserting different programs into the memory, the machine is made to carry out different computations. It was a fabulous idea—a single machine of fixed structure which, by making use of coded instructions stored in memory, could change itself, chameleon-like, from a machine dedicated to one task into a machine dedicated to a quite different one.

Turing showed that his universal machine is able to accomplish *any* task that can be carried out by means of a rote method (hence the characterization 'universal'). Nowadays, when so many people possess a physical realization of the universal Turing machine, Turing's idea of a one-stop-shop computing machine might seem as obvious as the wheel. But in 1936, when engineers thought in terms of building different machines for different purposes, Turing's concept was revolutionary.

By the end of 1945, thanks to wartime developments in digital electronics, groups in Britain and in the United States had embarked on creating a universal Turing machine in hardware. Turing headed a group situated at the **National Physical Laboratory** (NPL) in Teddington, London. His technical report '**Proposed Electronic Calculator**', dating from the end of 1945 and containing his design for the **Automatic Computing Engine** (ACE), was the first relatively complete specification of an electronic stored-program digital computer.

In the United States the Hungarian-American mathematician **John von Neumann** shared Turing's dream of building a universal stored-program computing machine. Von Neumann had learned of the universal Turing machine before the war—he and Turing came to know each other during 1936-1938, when both were at **Princeton University**. Like Turing, von Neumann became aware of the potential of high-speed digital electronics as a result of wartime work. Von Neumann's 'First Draft of a Report on the **EDVAC**', completed in the spring of 1945, also set out a design for an electronic stored-program digital computer ('EDVAC' stood for 'Electronic Discrete Variable Computer'). Von Neumann's report, to which Turing referred in 'Proposed Electronic Calculator', was more abstract than Turing's, saying little about programming or electronics. **Harry Huskey**, the electronic engineer who subsequently drew up the first detailed hardware designs for the EDVAC, said that the information in von Neumann's report was of no help to him in this.[3] Turing, in contrast, supplied detailed circuit designs, full specifications of hardware units, specimen programs in machine code, and even an estimate of the cost of building the ACE.

Turing A smile for his centenary[3]

Part I of 'Alan Turing, Father of the Modern Computer' provides an overview of Turing's many major contributions to the development of the computer and computing—including his pioneering work in the areas now called **Artificial Intelligence** and **Artificial Life**.

Part II tells the story of Turing's ACE. This is simply one of the best tales in the history of computers. Right from the start there was a mismatch of visions. Turing saw himself as building 'a brain'. 'In working on the ACE', he said, 'I am more interested in the possibility of producing models of the action of the brain than in the practical applications to computing'. Turing's employers, on the other hand, thought the ACE would be Britain's national computer: a single machine that could satisfy the computing needs of 'the whole country'. Frustration and disappointment dominate the story. Woolly-minded administrators wasted the brilliant technological achievements of Turing and his group. There is a happy ending—but by that time Turing had turned his back on the ACE forever. Much of Part II is in the words of the original protagonists, drawn from documents of the time. (These and other historic documents are now available online in **The Turing Archive for the History of Computing**.)

Part III of 'Alan Turing, Father of the Modern Computer' is a digital facsimile of 'Proposed Electronic Calculator', Turing's 48-page report describing his revolutionary electronic computing machine. Turing's original illustrations are included. (A paper version of the report is available in the book ***Alan Turing's Automatic Computing Engine***.)

Alan Turing, Father of the Modern Computer

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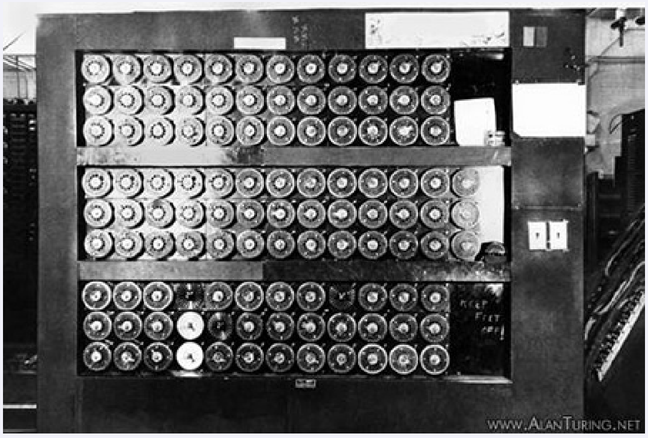
TIMELINE

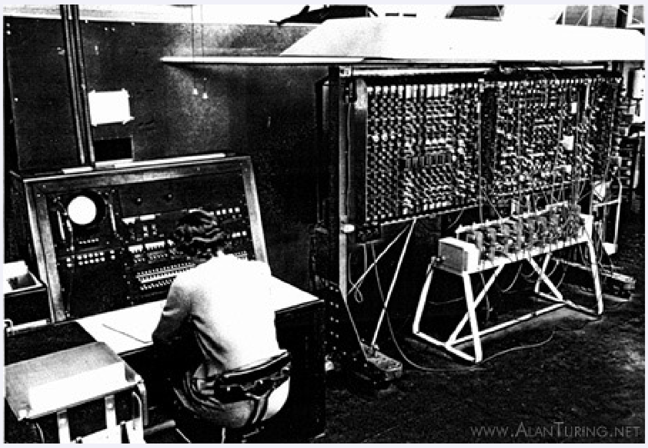
1936	The **universal Turing machine**
	Turing leaves **Cambridge** for the **Institute of Advanced Study** at Princeton, where he continues his pioneering work in recursion theory
1938	Turing returns to Cambridge
1939	At outbreak of war with Germany in September, Turing takes up residence at the Government Code and Cypher School, Bletchley Park
1940	First Turing **Bombe** is installed at Bletchley Park
1944	**Colossus**, the world's first large-scale electronic computer, is installed at Bletchley Park

1945	**Von Neumann**'s 'First Draft of a Report on the EDVAC' is circulated, setting out the design of the **EDVAC** (Electronic Discrete Variable Arithmetic Computer)
	Turing joins the **National Physical Laboratory**
	Turing's '**Proposed Electronic Calculator**' is circulated, setting out the design of the **ACE** (Automatic Computing Engine)
	Turing suggests (in 'Proposed Electronic Calculator') that computers will '**play very good chess**'
	ENIAC (Electronic Numerical Integrator and Computer) is the second large-scale electronic computer to operate
1946	Turing and his group **pioneer modern computer programming**, writing a library of sophisticated programs for the unbuilt ACE
	Turing presents a **course of lectures** on Versions V, VI, and VII of the ACE design, at the Ministry of Supply in London (Dec. 1946 to Feb. 1947). **Kilburn** attends from Manchester University
1947	Turing lectures on the ACE at **Burlington House** in London, the first public lecture to mention computer intelligence
	Darwin, Director of the National Physical Laboratory, halts work on **ACE Test Assembly**, leaving the field to Manchester
1948	Manchester wins the race: the world's **first stored-program electronic computer** comes to life on June 21 in **Newman**'s **Computing Machine Laboratory**
	Turing, now at Manchester as Deputy Director of the Computing Machine Laboratory, writes '**Intelligent Machinery**', the first manifesto of Artificial Intelligence
	Turing's and Champernowne's 'Turochamp' plays its **first game of chess**
	ENIAC is set up to run in (read-only) stored-program mode
1949	Four more electronic stored-program computers become operational: **EDSAC** (Electronic Delay Storage Automatic Calculator) at the University of Cambridge, followed by BINAC (Binary Automatic Computer) in the U.S., the CSIR Mark I (Council for Scientific and Industrial Research Mark I Computer) in Australia, and Whirlwind I in the U.S.
	Turing's paper 'Checking a Large Routine' inaugurates the area now known as 'program verification'
1950	**Pilot Model ACE** is operational, preceded in the U.S. by SEAC (National Bureau of Standards Eastern Automatic Computer) and followed by **SWAC** (National Bureau of Standards Western Automatic Computer)
	Turing publishes 'Computing Machinery and Intelligence', proposing the 'imitation game' or **Turing Test**
1951	The **Ferranti Mark I** is the first commercially-available electronic stored-program computer. The first off the production line is installed at Manchester University
	Turing begins using the Ferranti Mark I to **study biological growth**
	UNIVAC is the first commercially-available electronic stored-program computer in the U.S.
	von Neumann's computer at the Princeton **Institute for Advanced Study** is operational
	Oettinger at Cambridge University writes the first program capable of learning
1952	**EDVAC** is operational in the US
	Strachey's draughts (checkers) program plays its first game on the Manchester computer
1953	Turing publishes his classic paper on computer chess
1954	Turing dies at his home in mysterious circumstances, age 41
	The world's first single-user desk-side computer, the **G15**, is operational in California
1955	First **DEUCE**, production version of the Pilot Model ACE, is installed at the National Physical Laboratory
1956	**Dartmouth** Summer Research Project on Artificial Intelligence
1958	**Big ACE** operational at the National Physical Laboratory

The Mansion, Bletchley Park. Wartime headquarters of the Government Code and Cypher School.[4]



The Bombe. Turing's Bombes turned Bletchley Park into a codebreaking factory.[5]



The Pilot Model ACE[6]

Alan Turing, Father of the Modern Computer

Part I

Turing's Role in the History of Computing

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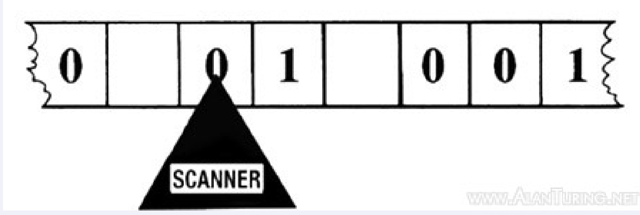
1. The Universal Turing Machine

Turing introduced his abstract Turing machines in his first major publication, 'On Computable Numbers, with an Application to the Entscheidungsproblem' (1936).[4] (Turing referred to these simply as 'computing machines'—the American logician Alonzo Church dubbed them 'Turing machines'.[5]) 'On Computable Numbers' pioneered the idea essential to the modern computer—the concept of controlling a computing machine's operations by means of a program of coded instructions stored in the machine's memory. This work had a profound influence on the development in the 1940s of the electronic stored-program digital computer, an influence often neglected or denied by historians of the computer.

King's College, Cambridge. Here Turing wrote 'On Computable Numbers'. Photo © Andrew Pearce, **Fotogenix.co.uk**

A Turing machine is an abstract conceptual model. It consists of a scanner and a limitless memory-tape. The tape is divided into squares, each of which may be blank or may bear a single symbol ('0' or '1', for example, or some other symbol taken from a finite alphabet). The scanner moves back and forth through the memory, examining one square at a time (the 'scanned square'). It reads the symbols on the tape and writes further symbols. The tape is both the memory and the vehicle for input and output. The tape may also contain a program of instructions. The tape itself is limitless—in fact Turing's aim was to show that there are tasks that Turing machines cannot perform, even given unlimited working memory and unlimited time.

A Turing machine has a small repertoire of basic operations: *move left one square*, *move right one square*, *print*, and *change state*. Movement is always by one square at a time. The scanner can print a symbol on the scanned square (after erasing any existing symbol). By changing its state the machine can, as Turing put it, 'remember some of the symbols which it has "seen" (scanned) previously'.[6] Turing did not specify a mechanism for changing state—Turing machines are abstractions and proposing a specific mechanism is unnecessary—but one can easily be imagined. Suppose that a device within the scanner consists of a dial with a finite number of positions, labelled 'a', 'b', 'c', and so on, each position counting as a different state. Changing state consists in shifting the dial's pointer from one labelled position to another. This device functions as a simple memory; for example, a dial with three positions can be used to record whether the square that the scanner has just vacated contained '0' or '1', or was blank.



The scanner and tape

The operation of the machine is governed by (what Turing called) a table of instructions. He gave the following simple example.[7] A machine—call it M—begins work with an endless blank tape and with the scanner positioned over any square of the tape. M has four states, labelled '**a**', '**b**', '**c**', and '**d**', and is in state **a** when it starts work. In the table shown, 'R' is an abbreviation of the instruction 'move right one square', 'P[0]' is an abbreviation of 'print 0 on the scanned square', and analogously 'P[1]'. The top line of the table reads: if you are in state **a** and the square you are scanning is blank, then print 0 on the scanned square, move right one square, and go into state **b**.

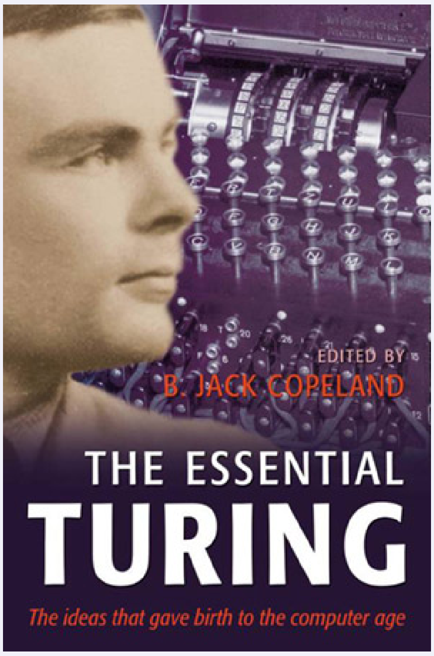
STATE	SCANNED SQUARE	OPERATIONS	NEXT STATE
a	blank	P[0], R	**b**
b	blank	R	**c**
c	blank	P[1], R	**d**
d	blank	R	**a**

An instruction table or 'program' for a Turing machine

Acting in accordance with this table of instructions—or program—M prints alternating binary digits on the tape, 0 1 0 1 0 1..., working endlessly to the right from its starting place, leaving a blank square in between each digit.

The UTM

The UTM (universal Turing machine) is universal in the sense that it can be programmed to carry out any calculation that could in principle be performed by a 'human computer'—a clerk who works in accordance with an 'effective' or rote procedure. Before the advent of the electronic computer, many thousands of human computers were employed in business, government, and research establishments. The universal machine has a single, fixed table of instructions built into it —'hard-wired', so to speak, into the machine. Operating in accordance with this one fixed table, the UTM can read and execute coded instructions inscribed on its tape. This is the 'stored program' concept, the idea of controlling the function of the computing machine by storing a program of instructions in the machine's memory.



The Essential Turing (Oxford University Press, 2004, ed. Copeland) gives a full account of how Turing machines work, and also of the Bletchley Park codebreaking operation and Turing's work on Enigma, including Turing's own description of the Bombe.

An instruction table for carrying out a desired task is placed on the UTM's tape in a suitably encoded form, the first line of the table occupying the first so many squares of the tape, the second line the next so many squares, and so on. (Turing referred to this encoded form of the instructions as the 'standard description' of the instruction table.) The UTM reads the instructions and carries them out on its tape. Different programs can be inscribed on the tape, enabling the UTM to carry out any task for which a Turing-machine instruction table can be written—thus a single machine of fixed structure is able to carry out every computation that can be carried out by any Turing machine whatsoever.

In 1936 the UTM existed only as an idea. But right from the start Turing was interested in the possibility of actually building such a machine.[8] His wartime acquaintance with electronics was the key link between his earlier theoretical work and his 1945 design for an electronic stored-program digital computer.

2. Codebreaking in World War II

Turing completed the logical design of the famous **Bombe**—built to break German Enigma messages—in the last months of 1939.[9] His designs were handed over to Harold 'Doc' Keen at the British Tabulating Machine Company in Letchworth, where the engineering development was carried out.[10] The first bombe, named 'Victory', was installed at the Government Code and Cypher School (GC & CS) at **Bletchley Park** early in 1940 and an improved model 'Agnus Dei' (later corrupted to 'Agnes' and 'Aggie') was installed in the summer of that year.[11] Agnus contained Gordon Welchman's ingenious 'diagonal board'.

Enigma machine with its wheels, lamps and plugboard exposed. Once the operator has inserted the correct wheels for the day he closes the inner lid.[8]

The Bombe was a 'computing machine'—a term for any machine able to do work that could in principle be done by a human computer—but one with a very narrow and specialized purpose, namely searching through the wheel-positions of the Enigma machine, at superhuman speed, in order to find the positions at which a German message had been encrypted. The Bombe produced likely candidates, which were tested by hand on an Enigma machine (or a replica of one)—if German text emerged (even a few words followed by nonsense), the candidate settings were the right ones.

The Bombe was based on the electromagnetic relay, although some later versions were electronic (i.e. based on valves or vacuum tubes) and in consequence faster. Relays are small switches consisting of a moving metal rod which opens and closes an electrical circuit; the rod is moved by means of a magnetic field. Electronic valves (called 'vacuum tubes' in the U.S.) operate very many times faster than relays, since the valve's only moving part is a beam of electrons.

During the attack on Enigma, Bletchley Park approached the **Post Office Research Station** at Dollis Hill in London to build a relay-based machine for use in conjunction with the Bombe. Once the Bombe had uncovered the Enigma settings used to encrypt a particular message, these settings were to be transferred to the proposed machine, which would then automatically decipher the message and print out the original German text.[12] Dollis Hill sent engineer Thomas Flowers to Bletchley Park. In the end, the machine Flowers built was not used, but he was soon to become one of the great figures of World War II codebreaking. Thanks to his pre-war research, Flowers was (as he himself remarked) possibly the only person in Britain who realized that valves could be used on a large scale for high-speed digital computing.[13]

Thomas H. Flowers, creator of Colossus[9]

The world's first large-scale electronic digital computer, Colossus, was designed and built during 1943 by Flowers and his team at Dollis Hill, in consultation with the Cambridge mathematician **Max Newman**, head of the section at Bletchley Park known simply as the 'Newmanry'.[14] (Turing had attended Newman's lectures on mathematical logic at Cambridge before the war; these lectures launched Turing on the research that led to his 'On Computable Numbers'.[15]) Colossus was operational at the beginning of 1944,[16] two years before the first comparable U.S. machine, the **ENIAC**, was working[17]. It was used against the Lorenz cipher machine, more advanced than Enigma and introduced in 1941.

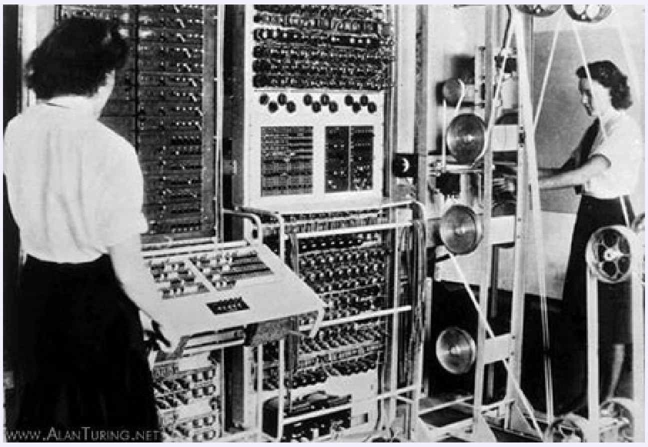
Turing had briefly joined the attack on the Lorenz machine in 1942, devising a cryptanalytical method known simply as 'Turingery'. Turingery was the third of the three strokes of genius that Turing contributed to the attack on the German codes—the others being his design for the Bombe and unravelling of the form of Enigma used by the Atlantic U-boats (see *The Essential Turing*). As fellow codebreaker Jack Good observed, 'I won't say that what Turing did made us win the war, but I daresay we might have lost it without him'.[18]

Turingery was a hand method, involving paper, pencil and eraser.

Basic to Turingery was the idea of forming what was called the 'delta' of a stream of letters. The delta of a letter-stream is the stream that results from adding together each pair of adjacent letters (Turingery and delta-ing are both explained in detail in ***Colossus: The Secrets of Bletchley Park's Codebreaking Computers***). Turing discovered that delta-ing would reveal information that was otherwise hidden. His discovery was essential to the developments that followed: the algorithms implemented in Colossus (and in its precursor **Heath Robinson**) depended on this simple but brilliant observation. In that sense, the entire machine-based attack on the Lorenz machine flowed from this fundamental insight of Turing's.

The Lorenz *Schlüsselzusatz* (cipher attachment) was code-named 'Tunny' by the British[10]

The British government kept Colossus secret: before the 1970s few had any idea that electronic computation had been used successfully during World War II, and it was not until 2000 that the British and the U.S. finally declassified the complete account of Colossus' wartime role.[19] So it was that, in the decades following the war, von Neumann and others told the world that the ENIAC was 'the first electronic computing machine'.[20] (In fact, what was arguably the first small-scale electronic computer was put together at Iowa State College by John Atanasoff and his student Clifford Berry.[21] Their tiny digital computer contained approximately 300 valves, compared to Colossus's 2400. Designed for one very specific mathematical task (solving systems of linear algebraic equations), Atanasoff's machine had virtually no programmability. Although its electronic circuits functioned, the computer as a whole never worked properly, because errors were introduced by an unsatisfactory binary card-reader. The computer was left unfinished in 1942 when Atanasoff moved away from Iowa State College.)

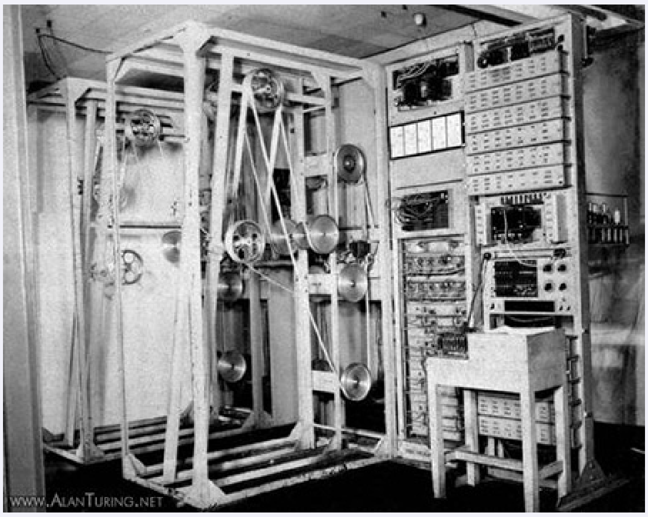


Colossus and two operators, Dorothy Du Boisson (left) and Elsie Booker[11]

Flowers had established decisively and for the first time that large-scale electronic computing machinery was practicable. However, while Colossus possessed a considerable amount of flexibility, it was far from universal. Nor did it store instructions internally. As with the later ENIAC, in order to set Colossus up for a new job it was necessary to modify some of the machine's wiring manually, by means of plugs and switches. During the construction of Colossus, Newman showed Flowers Turing's 'On Computable Numbers', with the key idea of storing coded instructions in memory, but Flowers did not follow it up.

Flowers has said that, once Turing saw Colossus in operation, it was just a matter of Turing's waiting to see what opportunity might arise to put the idea of his universal computing machine into practice.[22] There is little doubt that by 1944 Newman too had firmly in mind the possibility of building a universal machine using electronic technology. In February 1946, a few months after his appointment as Professor of Mathematics at the University of Manchester, Newman wrote to von Neumann in the U.S.:

> **I am ... hoping to embark on a computing machine section here, having got very interested in electronic devices of this kind during the last two or three years. By about eighteen months ago I had decided to try my hand at starting up a machine unit when I got out... . I am of course in close touch with Turing.**[23]



Robinson, precursor to Colossus. This machine, which eventually came to be known as 'Old Robinson', replaced the original 'Heath Robinson' (the two were similar in appearance).[12]

Newman's story is continued in chapter 11 **The Manchester Computer**. Turing's own opportunity came when **John Womersley** appeared out of the blue: see chapter 15 **Womersley Recruits Turing to the National Physical Laboratory**. By then Turing had taken pains to educate himself in electronic engineering (during the later part of the war he himself gave a series of evening lectures 'on valve theory').[24]

3. Turing's Design for the Automatic Computing Engine (ACE)

Turing saw that speed and memory were the keys to computing (in the words of his assistant at the NPL, **Jim Wilkinson**, Turing was 'obsessed with the idea of speed on the machine'[25]). Turing's design for the ACE had much in common with today's RISC (Reduced Instruction Set Computer) architectures and called for a high-speed memory of roughly the same capacity as an early Apple Macintosh computer and enormous by the standards of his day.

Turing's ACE and the **EDVAC—**which was not completed until 1952[26] — differed fundamentally in design. The EDVAC had (what is now called) a central processing unit or cpu, whereas in the ACE the different temporary stores and other memory locations had specific logical or numerical functions, e.g. addition, associated with them. For example, if two numbers were transferred to a certain named destination in memory, their sum would be formed there (ready to be transferred elsewhere by a subsequent instruction). Unlike the EDVAC with its cpu, in the ACE there was no single place where all the logical and numerical operations were done.

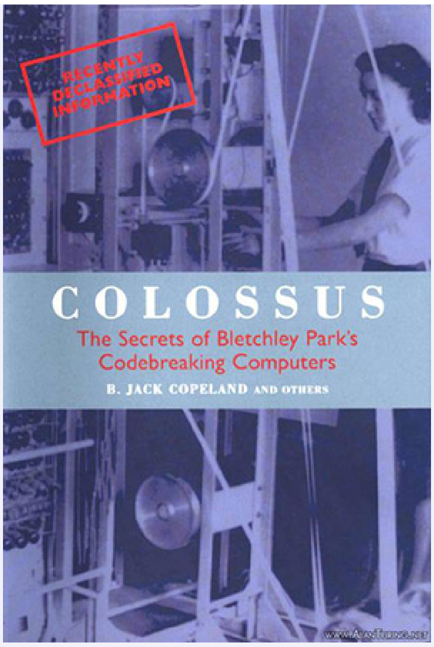
The ACE's programs were made up entirely of instructions like 'Transfer the contents of Temporary Store 15 to Temporary Store 16'. Instead of writing mathematically significant instructions such as

ADD x to y AND STORE THE RESULT IN z
or
MULTIPLY x BY y AND STORE THE RESULT IN z

someone programming the ACE had to compose a series of 'low-level' transfer instructions producing the same effect. A related difference between the ACE and the EDVAC was that, in Turing's design, complex behaviour was to be achieved by complex programming rather than by complex equipment. Turing's philosophy was to dispense with additional hardware (such as a multiplier, divider, and hardware for floating-point arithmetic) in favour of software, and he spoke disparagingly of 'the American tradition of solving one's difficulties by means of much equipment rather than thought'.[27]

In order to increase the speed of a program's execution, Turing proposed that instructions be stored, not consecutively in memory, but at carefully chosen positions, with each instruction containing a reference to the position of the next. This meant that each instruction was available at exactly the moment it was required, with no delays. Also with a view to speed, he included a small fast-access memory for the temporary storage of whichever numbers were most frequently used at a given stage of a computation. According to Wilkinson in 1955, Turing was 'the first to realise that it was possible to overcome access time difficulties with ... mercury lines ... or drum stores by providing a comparatively small amount of fast access store. Many of the commercial machines in the USA and ... in this country make great use of this principle.'[28]

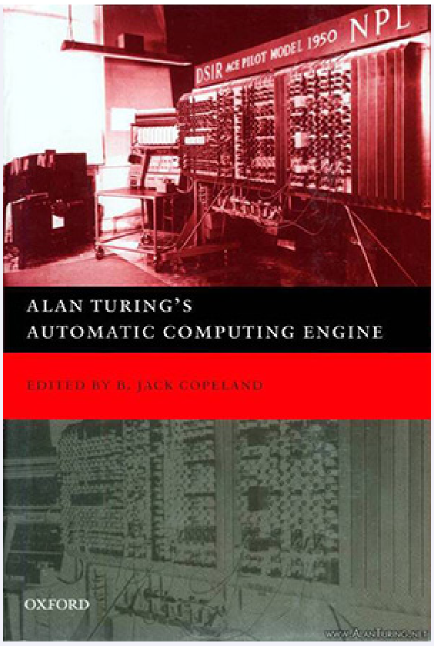
Administrative delays at the NPL (described in **Part II**) meant that it was several years after the completion in 1945 of Turing's design paper '**Proposed Electronic Calculator**' before any significant progress was made on the physical construction of the ACE. While waiting for the hardware to be built, Turing and his group pioneered the science of computer programming, writing a library of



For the full story of Colossus see **Colossus: The Secrets of Bletchley Park's Codebreaking Computers** (Oxford University Press, 2006, ed. Copeland). Contains two chapters by Flowers and first-hand accounts by 16 of the Bletchley Park codebreakers.

Bushy House, part of the National Physical Laboratory. The Pilot Model of the Automatic Computing Engine was built here in what was originally the butler's pantry.[13]

sophisticated mathematical programs for the planned machine (see chapter 17 **Turing Pioneers Computer Programming**). Early in 1947 members of Turing's group began to construct a minimal version of the ACE called the Test Assembly (see chapter 19 **Second Attempt to Build the ACE: the Huskey Era and the Test Assembly**). Unfortunately, work on this small computer was stopped later that year by the NPL's inept management. Had the project continued, the Test Assembly would probably have become the world's first functioning electronic stored-program computer—an honour that in the event went to the Manchester 'Baby', itself a very limited machine (see chapter 11 **The Manchester Computer**).



For more information about the ACE, see **Alan Turing's Automatic Computing Engine: The Master Codebreaker's Struggle to Build the Modern Computer** (Oxford University Press, 2005, ed. Copeland). Contains material by Turing and his contemporaries.

4. The ACE as Descendant of the Universal Turing Machine

Notoriously, Turing's universal machine of 1936 received no explicit mention in 'Proposed Electronic Calculator' and some have questioned whether the universal machine was an ancestor of the ACE at all. However, some fragmentary notes by Turing cast light on this issue. The notes are pages from a draft of 'Proposed Electronic Calculator', and in them Turing related the ACE to the universal Turing machine. He explained why the memory arrangement described in 'On Computable Numbers' could not 'be taken over as it stood to give a practical form of machine'. (The notes are in *Alan Turing's Automatic Computing Engine*.)

In a lecture given in 1947 Turing made it clear that he regarded the ACE as a 'practical version' of the universal Turing machine:

> **Some years ago I was researching on what might now be described as an investigation of the theoretical possibilities and limitations of digital computing machines. I considered a type of machine which had a central mechanism, and an infinite memory which was contained on an infinite tape ... It can be shown that a single special machine of that type can be made to do the work of all... . The special machine may be called the universal machine; it works in the following quite simple manner. When we have decided what machine we wish to imitate we punch a description of it on the tape of the universal machine... . The universal machine has only to keep looking at this description in order to find out what it should do at each stage. Thus the complexity of the machine to be imitated is concentrated in the tape and does not appear in the universal machine proper in any way... . [D]igital computing machines such as the ACE ... are in fact practical versions of the universal machine. There is a certain central pool of electronic equipment, and a large memory. When any particular problem has to be handled the appropriate instructions for the computing process involved are stored in the memory of the ACE ...** [29]

Turing[14]

A letter from Turing to the cyberneticist W. Ross Ashby again highlights the fundamental point of similarity between the ACE and the universal Turing machine:

> **The ACE is in fact, analogous to the 'universal machine' described in my paper on**

computable [sic] numbers ... [W]ithout altering the design of the machine itself, it can, in theory at any rate, be used as a model of any other machine, by making it remember a suitable set of instructions.[30]

5. The ACE and the American EDVAC

In the years immediately following the Second World War John von Neumann made the concept of the stored-program digital computer widely known, through his writings and charismatic public addresses. Von Neumann wrote 'First Draft of a Report on the EDVAC' and subsequently directed the computer project at the Princeton Institute of Advanced Study. The ensuing machine, the **IAS computer**, although not the first to run in the U.S. (it began work in the summer of 1951[31]), was the most influential of the early U.S. computers and the precursor to the IBM 701, the company's first mass-produced stored-program electronic computer.

Von Neumann's 'First Draft of a Report on the EDVAC' was widely read.[32] Turing certainly expected readers of his 'Proposed Electronic Calculator' to be familiar with the 'First Draft'. At the end of the first section of '**Proposed Electronic Calculator**' he said:

The present report gives a fairly complete account of the proposed calculator. It is recommended however that it be read in conjunction with J. von Neumann's '[First Draft of a] Report on the EDVAC'.

To what extent was the content of 'Proposed Electronic Calculator' influenced by the 'First Draft' (which preceded it by a few months)? Turing's paper follows von Neumann's terminology and notation to some extent—a sensible decision, making it more likely that Turing's report would be readily understood. In order to depict the EDVAC's logic gates, von Neumann had used a modified version of a diagrammatic notation introduced by **McCulloch** and **Pitts** in connection with neural nets.[33] Turing adopted this modified notation and in fact considerably extended it.[34] There is no doubt that Turing simply borrowed some of the more elementary material from the 'First Draft'. For example, his diagram of an adder (**figure 10** of 'Proposed Electronic Calculator') is essentially the same as von Neumann's figure 3.[35] A newspaper report in 1946 said that Turing 'gives credit for the donkey work on the A.C.E. to Americans'.[36]

However, Turing's logic diagrams provide detailed designs for the logical control and the arithmetic part of the calculator and go far beyond anything to be found in the 'First Draft'. The similarities between 'Proposed Electronic Calculator' and the 'First Draft' are relatively minor in comparison to the striking differences in the designs that they contain. Moreover, von Neumann's minor influence on 'Proposed Electronic Calculator' should not be allowed to mask the extent to which Turing's universal machine of 1936 was itself a fundamental influence upon von Neumann.

6. Turing's Influence on EDVAC Pioneer John von Neumann

In the secondary literature, von Neumann is often said to have invented the stored-program computer, but he repeatedly emphasized that the fundamental conception was Turing's.[37] Von Neumann became familiar with ideas in 'On Computable Numbers' during Turing's time at Princeton (1936-38). He was soon intrigued by Turing's concept of a universal computing machine.[38] It was von Neumann who placed Turing's concept into the hands of American engineers. Stanley Frankel (the Los Alamos physicist responsible, with

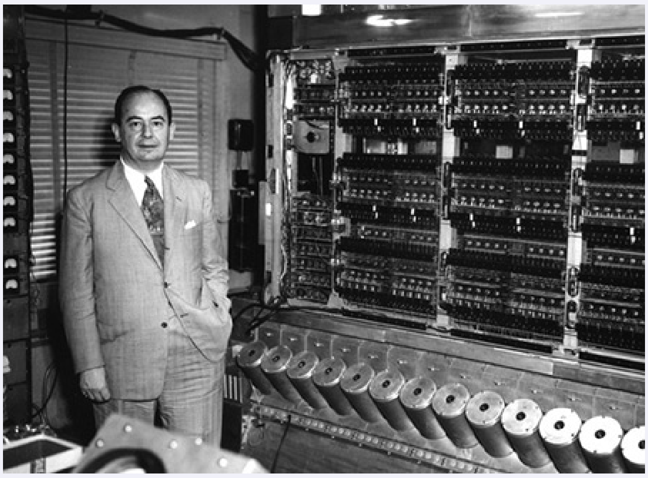
King's College, Cambridge, birthplace of the universal Turing machine and the stored program concept. Photo © Andrew Pearce, **Fotogenix.co.uk**

Kite Sharpless and the EDVAC (Philadelphia Evening Bulletin, 3 March 1947) von Neumann and others, for mechanizing the large-scale calculations involved in the design of the atomic and hydrogen bombs) recorded von Neumann's view of the importance of 'On Computable Numbers':

> **I know that in or about 1943 or '44 von Neumann was well aware of the fundamental importance of Turing's paper of 1936 'On computable numbers ...', which describes in principle the 'Universal Computer' of which every modern computer (perhaps not ENIAC as first completed but certainly all later ones) is a realization. Von Neumann introduced me to that paper and at his urging I studied it with care. Many people have acclaimed von Neumann as the 'father of the computer' (in a modern sense of the term) but I am sure that he would never have made that mistake himself. He might well be called the midwife, perhaps, but he firmly emphasized to me, and to others I am sure, that the fundamental conception is owing to Turing - insofar as not anticipated by Babbage, Lovelace, and others. In my view von Neumann's essential role was in making the world aware of these fundamental concepts introduced by Turing and of the development work carried out in the Moore school and elsewhere.**[39]

John von Neumann[15]

In 1944, von Neumann joined the Eckert-Mauchly ENIAC group at the Moore School of Electrical Engineering at the University of Pennsylvania. (At that time he was involved in the Manhattan Project at Los Alamos, where roomfuls of clerks armed with desk calculating machines were struggling to carry out the massive calculations required by the physicists.) ENIAC—which had been under construction since 1943—was, as mentioned above, not a stored-program computer; instead programming consisted of re-routing cables and setting switches. Moreover, the ENIAC was far from universal, having been designed with only one very specific task in mind, the calculation of trajectories of artillery shells.



von Neumann beside the IAS computer at Princeton. The row of cannisters is the high-speed memory. Each cannister contains a single cathode ray tube known as a 'Williams tube' after its inventor, F. C. Williams.[16]

Von Neumann brought his knowledge of 'On Computable Numbers' to the practical arena of the Moore School. Thanks to Turing's abstract logical work, von Neumann knew that, by making use of coded instructions stored in memory, a single machine of fixed structure can in principle carry out any task for which a program can be written. When ENIAC engineer Presper Eckert described his idea of using the mercury delay line as a high-speed recirculating memory, von Neumann saw that this was the means to make concrete the abstract universal computing machine of 'On Computable Numbers'.[40] (Turing explains mercury delay line memory on **pages 4-5** of Part III.)

When, in 1946, von Neumann established his own project to build a stored-program computer at the Institute for Advanced Study, he gave his engineers 'On Computable Numbers' to read.[41] **Julian Bigelow**, von Neumann's chief engineer and largely responsible for the engineering design of the computer built at the Institute, said:

> **The person who really ... pushed the whole field ahead was von Neumann, because he understood logically what [the stored-program concept] meant in a deeper way than anybody else... . The reason he understood it is because, among other things, he**

> **understood a good deal of the mathematical logic which was implied by the idea, due to the work of A. M. Turing ... in 1936-1937 ... . Turing's [universal] machine does not sound much like a modern computer today, but nevertheless it was. It was the germinal idea. ... So ... [von Neumann] saw ... that [the ENIAC] was just the first step, and that great improvement would come.**[42]

Von Neumann repeatedly emphasized the fundamental importance of 'On Computable Numbers' in lectures and in correspondence. In 1946 he wrote to the mathematician Norbert Wiener of 'the great positive contribution of Turing'—Turing's mathematical demonstration that 'one, definite mechanism can be "universal"'.[43] In 1948, in a lecture entitled 'The General and Logical Theory of Automata', von Neumann said:

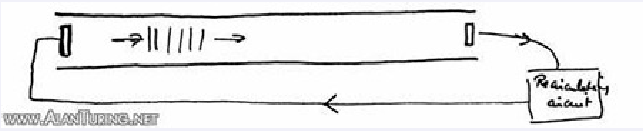
> **The English logician, Turing, about twelve years ago attacked the following problem. He wanted to give a general definition of what is meant by a computing automaton... . Turing carried out a careful analysis of what mathematical processes can be effected by automata of this type... . He ... also introduce[d] and analyse[d] the concept of a 'universal automaton' ... An automaton is 'universal' if any sequence that can be produced by any automaton at all can also be solved by this particular automaton. It will, of course, require in general a different instruction for this purpose. *The Main Result of the Turing Theory*. We might expect a priori that this is impossible. How can there be an automaton which is at least as effective as any conceivable automaton, including, for example, one of twice its size and complexity? Turing, nevertheless, proved that this is possible.**[44]

The following year, in a lecture delivered at the University of Illinois entitled 'Rigorous Theories of Control and Information', von Neumann said:

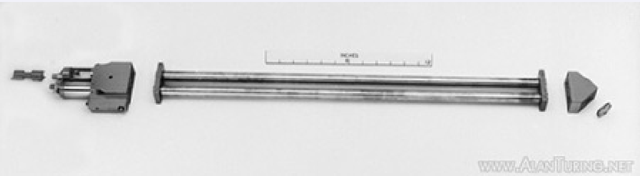
> **The importance of Turing's research is just this: that if you construct an automaton right, then any additional requirements about the automaton can be handled by sufficiently elaborate instructions. This is only true if [the automaton] is sufficiently complicated, if it has reached a certain minimal level of complexity. In other words ... there is a very definite finite point where an automaton of this complexity can, when given suitable instructions, do anything that can be done by automata at all.**[45]

Many books on the history of computing in the U.S. make no mention of Turing. No doubt this is in part explained by the absence of any explicit reference to Turing's work in the series of technical reports in which von Neumann, with various co-authors, set out a logical design for an electronic stored-program digital computer.[46] Nevertheless there is evidence in these documents of von Neumann's knowledge of Turing's 'On Computable Numbers'. For example, in the report

The ENIAC. Although standardly described as the 'first electronic computer', the ENIAC in fact went into operation two years later than Colossus.[17]



Turing's 1947 sketch of a mercury delay line[18]



Type of mercury delay line known as a 'trombone'[19]

The Princeton Institute for Advanced Study, home of von Neumann's computer project. Photo © Thomas Uphill.

entitled 'Preliminary Discussion of the Logical Design of an Electronic Computing Instrument' (1946), von Neumann and his co-authors, Arthur Burks and Herman Goldstine (former members of the ENIAC group who had joined von Neumann at the Institute for Advanced Study) wrote the following:

First Remarks on the Control and Code:

> **It is easy to see by formal-logical methods, that there exist codes that are in abstracto adequate to control and cause the execution of any sequence of operations which are individually available in the machine and which are, in their entirety, conceivable by the problem planner. The really decisive considerations from the present point of view, in selecting a code, are more of a practical nature: Simplicity of the equipment demanded by the code, and the clarity of its application to the actually important problems together with the speed of its handling of those problems.**[47]

Burks has confirmed that the first sentence of this passage is a reference to the universal Turing machine.[48] (The report was not intended for formal publication and no attempt was made to indicate those places where reference was being made to the work of others.)

The passage just quoted is in fact an excellent summary of the situation at that time. In 'On Computable Numbers' Turing had shown in abstracto that, by means of instructions expressed in the programming code of his 'standard descriptions', a single machine of fixed structure is able to carry out any task that a 'problem planner' is able to analyse into effective steps. By 1945, considerations in abstracto had given way to the practical problem of devising an equivalent programming code that could be implemented efficiently by means of electronic circuits. Von Neumann's embryonic code appeared in the 'First Draft'. 'Proposed Electronic Calculator' set out Turing's own very different and much more fully-developed code.

Turing[20]

von Neumann[21]

7. The Pilot Model ACE and the Production Model DEUCE

Had Turing's ACE been built as planned, it would have been in a different league from the other early computers, but his colleagues at the NPL thought the engineering work too ambitious and a considerably smaller machine was built. Known as the **Pilot Model ACE**, this machine ran its first program on 10 May 1950. With a clock speed of 1 MHz it was for some time the fastest computer in the world. Despite having only a few per cent of the memory capacity that Turing had specified, the Pilot ACE in other respects adhered closely to what Turing called '**Version V**' of his ACE design.

The English Electric Company built a production version of the Pilot Model ACE called the '**DEUCE**' (Digital Electronic Universal Computing Engine). The first DEUCE was delivered in March 1955 (to the NPL). The DEUCE was a huge success and more than 30 were sold—confounding the suggestion made in 1946 by the Director of the NPL, Sir Charles Darwin, that 'it is very possible that ... one machine would suffice to solve all the problems that are demanded of it from the whole country'.[49] DEUCEs were used for many scientific, industrial and commercial applications, including (to name but a very few) aircraft design, atomic reactor design, atomic weapons research, financial analysis, calculation of income tax tables and other assorted tables, food industry work, map making, optimum siting of power stations, crystallography, spectroscopy, oil prospecting, and the simulation of complex systems (the first traffic flow simulations were carried out on the Pilot ACE). The last DEUCE went out of service in about 1970.

8. The ACE Family of Computers

The basic principles of Turing's ACE design were used in the G15 computer, built and marketed by the Detroit-based Bendix Corporation. The G15 was designed by **Harry Huskey**, who spent 1947 at the NPL, working in the ACE Section. The G15 was arguably the first personal computer. By following Turing's philosophy of minimizing hardware in favour of software, Huskey was able to make the G15 small enough (it was the size of a large domestic refrigerator) and cheap enough to be marketed as a single-user desk-side computer. Yet thanks to the ACE-like design, the G15 was as fast as computers many times its size. The first G15 ran in 1954.[50] Over 400 were sold worldwide and the G15 remained in use until about 1970.

The full-scale ACE was inaugurated in 1958 (see chapter 24 **The Big ACE**). Other derivatives of Turing's ACE design include the MOSAIC (Ministry of Supply Automatic Integrator and Computer), which played a role in Britain's air defences during the Cold War period, the E.M.I. Business Machine, a relatively slow electronic computer with a large memory (designed for the shallow processing of large quantities of data that is typically demanded by business applications) and the low-cost transistorized Packard-Bell PB250.[51]

von Neumann[22]

The MOSAIC

The MOSAIC[52], based on Version VII of Turing's logical design for the ACE, first ran a program in 1952 or early 1953.[53] William Chandler and Allen Coombs, Flowers' right-hand men from the Colossus days, carried out the engineering design for the MOSAIC (see chapter 18 **First Attempt to Build the ACE: the Flowers Era**). With a pulse rate of 570 kilo-Hertz (about half the speed of the ACE), the MOSAIC contained approximately 7000 valves and 2000 semi-conductors (germanium diodes).[54] Originally a high-speed memory of 96 mercury delay lines was planned[55]; in the final form of the machine there were 64 long delay lines and a handful of short delay lines, holding a total of 1030 40-digit words.[56] Of the various ACE-type computers that were built, the MOSAIC was (apart from its slower pulse rate) the closest to Turing's conception of the ACE.

The Pilot Model of Turing's Automatic Computing Engine. The Pilot ACE was the fastest of the early electronic computers.[23]

The MOSAIC was installed in 1954 or early 1955 at the Royal Radar Establishment in Malvern,[57] where it was used to calculate aircraft trajectories from radar data, in connection with anti-aircraft measures. (The details of the computer's use are still classified.) Two mobile automatic data-recorders operated in conjunction with a radar tracking system. Each recorder involved approximately 2000 valves, with special cathode-ray tube switches and pneumatic equipment to provide a record on punched paper tape.[58]

Given that two engineers working alone succeeded in completing the large MOSAIC (Coombs emphasized: 'it was just Chandler and I—we designed every scrap of that machine'[59]), there is in our view little doubt that, given sufficient manpower, a computer reasonably close to Turing's Version VII of the ACE could have been operational in the very early 1950s. Thanks to their wartime involvement with Colossus, Chandler and Coombs possessed unrivalled expertise in large-scale digital electronics and had a substantial lead on everyone else in the field. Turing, of course, was well aware of this, but the Official Secrets Act prevented him from sharing his knowledge of Colossus with Darwin, Director of the National Physical Laboratory. Had he been able to do so, the NPL might have acted to boost the meagre resources available to Chandler and Coombs, so bringing a version of the ACE to life much sooner.

The NPL DEUCE in 1958[24]

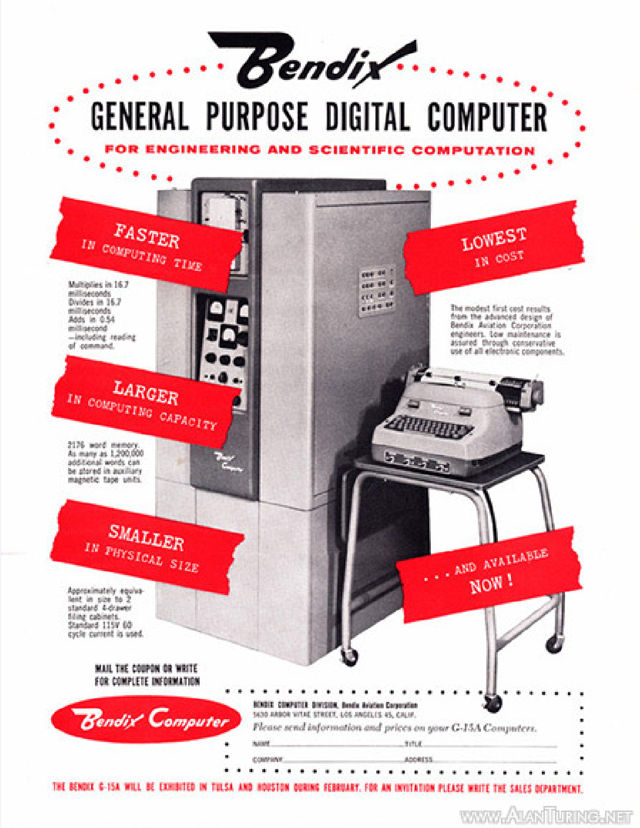
9. Turing and Artificial Intelligence (AI)

The myth

Artificial Intelligence is often said to have been born in the mid-1950s in the U.S. For example:

> **Artificial Intelligence, conceived at Carnegie Tech in the autumn of 1955, quickened by Christmas, and delivered on Johnniac in the spring, made a stunning debut at the conference from which it later took its name.**[60]

The AI program 'delivered on Johnniac' (a Californian copy of von Neumann's computer at the Institute for Advanced Study) was the Logic Theorist, written by Allen Newell, Herbert Simon, and Cliff Shaw and demonstrated at a conference, the Dartmouth Summer Research Project on Artificial Intelligence, held at Dartmouth College, New Hampshire.[61] The Logic Theorist was designed to prove theorems from Whitehead and Russell's *Principia Mathematica*.[62] In one case the proof devised by the Logic Theorist was several lines shorter than the one given by Whitehead and Russell; Newell, Simon, and Shaw wrote up the proof and sent it to the *Journal of Symbolic Logic*. This was almost certainly the first paper to have a computer listed as a co-author, but unfortunately it was rejected.[63]

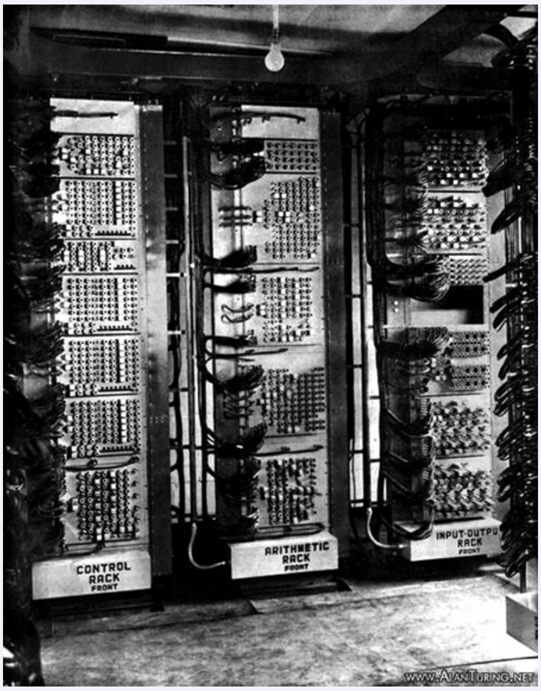


Advertisement for the Bendix G15, a desk-side computer based on Turing's ACE design[25]

The reality

In Britain the term 'machine intelligence' pre-dated 'artificial intelligence', and the field of enquiry itself can be traced much further back than 1955. If anywhere has a claim to be the birthplace of AI, it is Bletchley Park. Turing was the first to carry out substantial research in the area. At least as early as 1941 he was thinking about machine intelligence—in particular the possibility of computing machines that solved problems by means of searching through the space of possible solutions, guided by what would now be called 'heuristic' principles—and about the mechanization of chess.[64] At Bletchley Park, in his spare time, Turing discussed these topics and also machine learning. He circulated a typescript concerning machine intelligence among some of his colleagues.[65] Now lost, this was undoubtedly the earliest paper in the field of AI.

The first AI programs ran in Britain in 1951-52, at Manchester and Cambridge. This was due in part to the fact that the first stored-program electronic computers ran in Britain and in part to Turing's influence on the first generation of computer programmers. Even in the U.S., the Logic Theorist was not the first AI program to run. Arthur Samuel's Checkers (or Draughts) player first ran at the end of 1952 on the IBM 701, IBM's first stored-program computer.[66] In 1955 Samuel added learning to the program.



Three of MOSAIC's racks. A large computer built to Turing's design, the MOSAIC was used for secret work during the Cold War.[26]

The Bombe

The Bombe is the first milestone in the history of machine intelligence. Central to the Bombe was the idea of solving a problem by means of a guided mechanical search through the space of possible solutions. In this instance, the space of possible solutions consisted of configurations of the Enigma machine (in another case it might consist of configurations of a chess board). The Bombe's search could be guided in various ways; one involved what Turing called the 'multiple encipherment condition' associated with a crib (described in Chapter 6 of Turing's *Treatise on the Enigma*, written in the second half of 1940; this chapter is in *The Essential Turing* and the entire *Treatise* is available online in *The Turing Archive for the History of Computing* **<http://www.AlanTuring.net/profs_book>**). A search guided in this fashion, Turing said, would 'reduce the possible positions to a number which can be tested by hand methods'.[67] A crib is a word or phrase that the cryptanalyst believes might be part of the German message. For example, it might be conjectured that a certain message contains 'WETTER FUR DIE NACHT' (weather for the night). Many Enigma networks were good sources of cribs, thanks both to the stereotyped nature of German military messages and to lapses of cipher security. One station sent exactly the same message ('beacons lit as ordered') each evening for a period of several months.[68]

Dartmouth College, New Hampshire, venue of the Dartmouth Summer Research Project on Artificial Intelligence[27]

Modern AI researchers speak of the method of *generate-and-test*. Potential solutions to a given problem are generated by means of a guided search. These potential solutions are then tested by an auxiliary method to find out if any is actually a solution. Nowadays in AI both processes, generate and test, are typically carried out by the same program. The Bombe mechanized the first process. The testing of the potential solutions (the 'stops') was then carried out manually—by setting up a replica Enigma accordingly, typing in the cipher text, and seeing whether or not German words emerged.

Herb Simon and Al Newell, two of AI's pioneers[28]

Machine intelligence 1945-1948

In designing the ACE, machine intelligence was not far from Turing's thoughts—he described himself as building 'a brain'[69] and declared 'In working on the ACE I am more interested in the possibility of producing models of the action of the brain than in the practical applications to computing'.[70] On page 16 of '**Proposed Electronic Calculator**' he said:

> **'Can the machine play chess?' It could fairly easily be made to play a rather bad game. It would be bad because chess requires intelligence. We stated at the beginning of this section that the machine should be treated as entirely without intelligence. There are indications however that it is possible to make the machine display intelligence at the risk of its making occasional serious mistakes. By following up this aspect the machine could probably be made to play very good chess.**

(Turing's point was probably that the use of heuristic search brings with it the risk of the machine's sometimes making mistakes.)

Arthur Samuel, creator of the first AI program to run in the United States[29]

In February 1947 (in the rooms of the Royal Astronomical Society in Burlington House, London[71]) Turing gave what is, so far as is known, the earliest public lecture to mention computer intelligence, providing a breathtaking glimpse of a new field.[72] He described the human brain as a 'digital computing machine'[73] and discussed the prospect of machines that act intelligently, learn, and beat human opponents at chess. He stated that '[w]hat we want is a machine that can learn from experience' and that '[t]he possibility of letting the machine alter its own instructions provides the mechanism for this'.[74] The possibility of a computer's operating on and modifying its own program as it runs, just as it operates on the data in its memory, is implicit in the stored-program concept.

At the end of this lecture Turing set out what he later called the

'Mathematical Objection' to the view that minds are machines. This is now widely known as the Gödel argument, and has been made famous by Roger Penrose.[75] (In fact the objection originated with the mathematical logician Emil Post, as early as 1921.[76]) Turing proposed an interesting and arguably correct solution to the objection.[77]

In the middle of 1947, with little progress on the physical construction of the ACE, a thoroughly disheartened Turing applied for a twelve-month period of sabbatical leave to be spent in Cambridge. The purpose of the leave, as described by Darwin in July 1947, was to enable Turing to

> **extend his work on the [ACE] still further towards the biological side. I can best describe it by saying that hitherto the machine has been planned for work equivalent to that of the lower parts of the brain, and [Turing] wants to see how much a machine can do for the higher ones; for example, could a machine be made that could learn by experience? This will be theoretical work, and better done away from here.**[78]

Turing left the NPL for Cambridge in the autumn of 1947 (see chapter 21 **Turing Leaves the NPL**).

In the summer of 1948 Turing completed a report describing the outcomes of this research. It was entitled '**Intelligent Machinery**'.[79] Donald Michie recalls that Turing

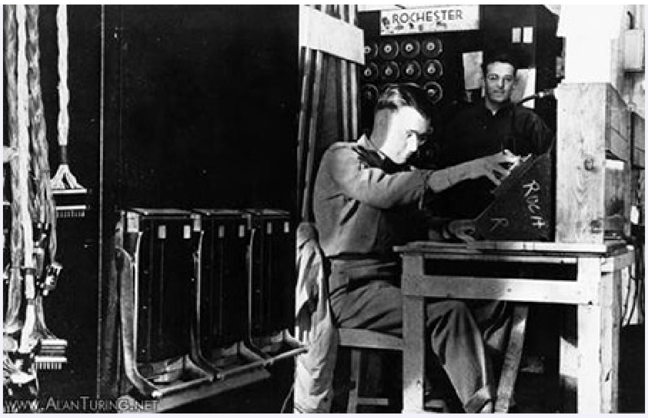
> **was in a state of some agitation about its reception by his superiors at N.P.L.: 'A bit thin for a year's time off!'.**[80]

The headmasterly Darwin—who once complained about the 'smudgy' appearance of Turing's work[81]—was, as Turing predicted, displeased with 'Intelligent Machinery', describing it as a 'schoolboy's essay'[82] and 'not suitable for publication'.[83] In reality this far-sighted paper was the first manifesto of Artificial Intelligence; sadly Turing never published it.

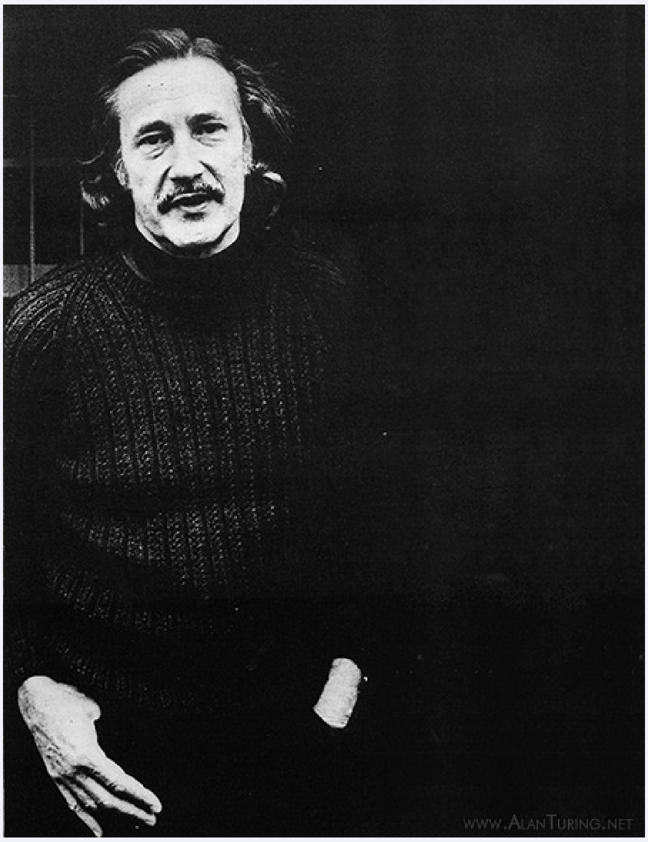
'Intelligent Machinery' is a wide-ranging and strikingly original survey of the prospects of AI. In it Turing brilliantly introduced a number of the concepts that were later to become central in AI, in some cases after reinvention by others. These included the logic-based approach to problem-solving, now widely used in expert systems, and, in a brief passage concerning what he called 'genetical or evolutionary search'[84], the concept of a genetic algorithm—important in both AI and **Artificial Life**. (The term 'genetic algorithm' was only introduced circa 1975.[85]) In the light of his work with the Bombe, it is no surprise to find Turing hypothesizing in 'Intelligent Machinery' that 'intellectual activity consists mainly of various kinds of search'.[86] Eight years later the same hypothesis was put forward independently by Newell and Simon and through their influential work[87] became one of the principal tenets of AI. 'Intelligent Machinery' also contains the earliest description of (a restricted form of) what Turing was later to call the 'imitation game' and is now known simply as the Turing test. It contains too his intriguing claim that the concept of intelligence is an 'emotional concept'.

The Turing test

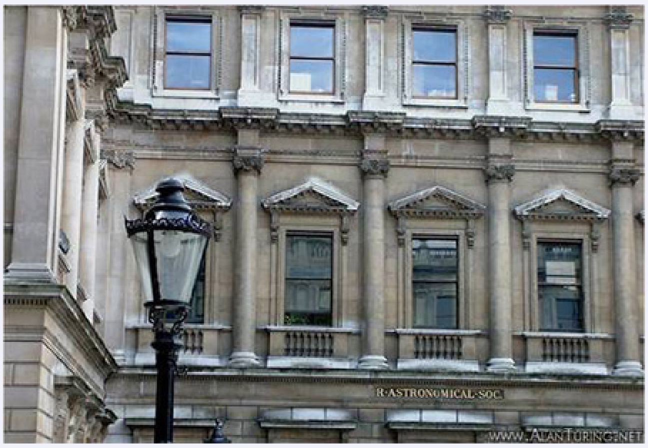
In his 1950 article 'Computing Machinery and Intelligence' Turing described an imitation game involving an interrogator and two subjects, one male (*A*) and one female (*B*). The interrogator



Working in a Bombe room at Outstation Eastcote. 'Menus' for outstation Bombes were received from Bletchley Park by teleprinter.[30]



Christopher Strachey. Strachey's draughts (checkers) player was the first computer program to incorporate heuristics.[31]



Burlington House, the venue of Turing's 1947 lecture[32] communicates with *A* and *B* from a separate room (nowadays this would probably be by means of a keyboard and screen); apart from this the three participants have no contact with each other. The interrogator's task is to find out, by asking questions, which of *A* and *B* is the man. *A*'s aim is that the interrogator make the wrong identification. As to *B*, Turing said 'The object of the game for the third player ... is to help the interrogator. The best strategy for her is probably to give truthful answers.'[88]

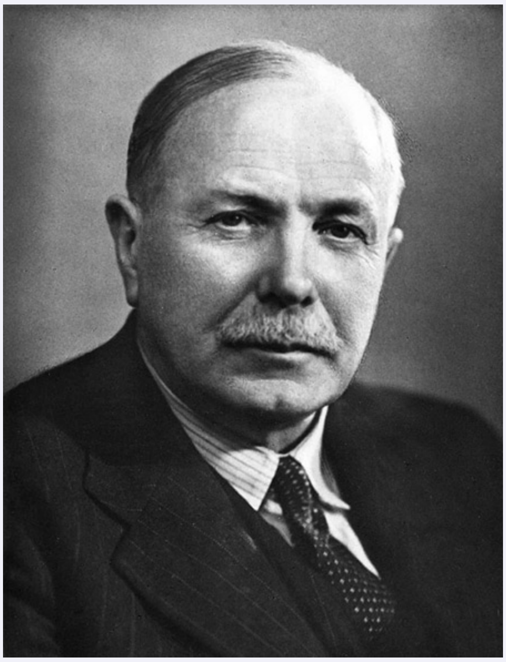
Turing then asked, 'What will happen when a machine takes the part of *A* in this game?'.[89] The game is now one in which a computer imitates a human being (man or woman). The interrogator's task is to discover which of *A* or *B* is the computer; to do so he or she is permitted to ask any question (or put any point) on any topic. The computer is allowed to do everything possible to force a wrong identification.

To assess the computer's performance, we ask:

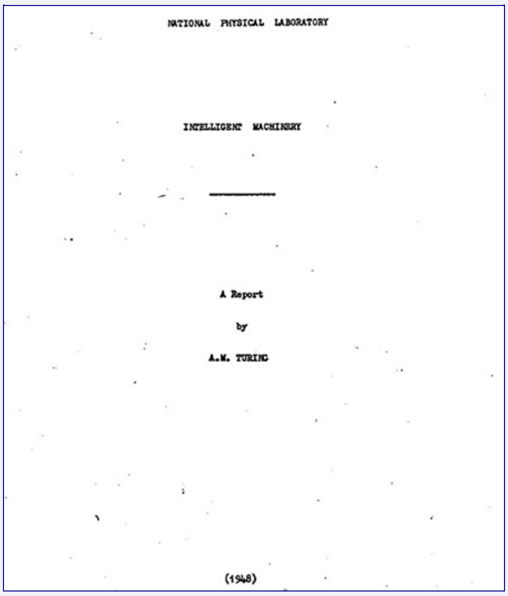
> **Will the interrogator decide wrongly as often when the [computer-imitates-human] game is played ... as he does when the game is played between a man and a woman?**[90]

If the computer (in the computer-imitates-human game) does no worse than the man (in the man-imitates-woman game), it succeeds in the game. The ability to play the imitation game successfully is Turing's proposed 'criterion for "thinking"'.[91] The role of the man-imitates-woman game is frequently misunderstood, however. The game is part of the protocol for *scoring* the test.[92] Will interrogators decide wrongly as often in man-imitates-woman imitation games as they do in computer-imitates-human games? This question, Turing said, replaces the question 'Can machines think?'.[93]

Some commentators claim that what Turing was doing in 'Computing Machinery and Intelligence' was presenting a test in which the computer is to impersonate a woman (rather than a human being), its degree of success being compared with a male player's degree of success at the same task. However, when describing his test in a radio broadcast Turing said that '[t]he idea of the test is that the machine has to try and pretend to be a man ... and it will pass only if the pretence is reasonably convincing';[94] and in yet another presentation of the test he said simply that the point of the test is to determine whether or not a computer can 'imitate a brain'.[95]



Charles Darwin, Director of the National Physical Laboratory[33]



NATIONAL PHYSICAL LABORATORY

INTELLIGENT MACHINERY

A Report

by

A.M. TURING

(1948)

The first manifesto of Artificial Intelligence (1948)

The first AI programs

Both during and after the war Turing experimented with machine routines for playing chess: in the absence of a computer, the machine's behaviour was simulated by hand, using paper and pencil. In 1948 Turing and David Champernowne, the mathematical economist, constructed the loose system of rules dubbed the 'Turochamp'.[96] Champernowne reported that his wife, a beginner at chess, took on the Turochamp and lost. Turing began to program the Turochamp for the Manchester **Ferranti Mark I** but unfortunately never completed the task.[97] He later published a classic early article on chess programming.[98]

Dietrich Prinz, who worked for Ferranti, wrote the first chess program to be implemented.[99] It ran in November 1951 on the Ferranti Mark I.[100] Unlike the Turochamp, Prinz's program could not play a complete game and operated by exhaustive search rather than under the guidance of heuristics. Prinz 'learned all about programming the Mark I computer at seminars given by Alan Turing and Cecily

Popplewell'.[101] Like Turing, he wrote a programming manual for the Mark I.[102] Prinz also used the Mark I to solve logical problems. (In 1949 and 1951 Ferranti built two small experimental special-purpose computers for theorem-proving and other logical work.[103])

Christopher Strachey's Draughts Player was—apart from Turing's 'paper' chess-players—the first AI program to use heuristic search. He coded it for the Pilot Model ACE in May 1951.[104] Strachey's first attempt to get his program running on the Pilot ACE was defeated by coding errors. When he returned to the NPL with a debugged version of the program, he found that a major hardware change had been made, with the result that the program would not run without substantial revision.[105] He finally got his program working on the Ferranti Mark I in mid-1952, with Turing's encouragement and utilizing the latter's recently completed *Programmer's Handbook*[106].[107] By the summer of 1952 the program could play a complete game of draughts at a reasonable speed.[108] The essentials of Strachey's program were taken over by **Arthur Samuel** in the U.S.[109]

The first AI programs to incorporate learning, written by Anthony Oettinger at the University of Cambridge, ran in 1951.[110] Oettinger wrote his 'response learning programme' and 'shopping programme' for the Cambridge **EDSAC** computer. Oettinger was considerably influenced by Turing's views on machine learning[111], and suggested that the shopping program—which simulated the behaviour of 'a small child sent on a shopping tour'[112]—could pass a version of the Turing test in which 'the questions are restricted to ... the form "In what shop may article *j* be found?" '[113].

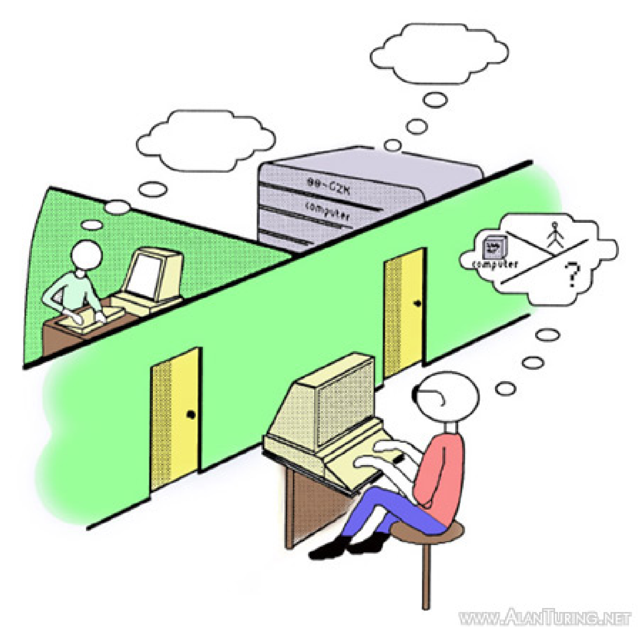
Turing's anticipation of connectionism

Turing did not only invent the concept of the stored-program digital computer; he also pioneered the idea of computing by artificial neural networks. The major part of his 1948 paper '**Intelligent Machinery**' is a discussion, anticipating the modern field of **connectionism**, of what Turing called 'unorganised machines'.[114]

Standard digital computers are superb number crunchers. Ask them to predict a rocket's trajectory or calculate the financial figures for a large multinational corporation, and they can churn out the answers in seconds. But seemingly simple actions that people routinely perform, such as recognising a face or reading handwriting, have proved extremely difficult to program. Perhaps the networks of neurons that make up the brain have a natural facility for such tasks that standard computers lack.

Connectionism, still in its infancy, is the science of computing with networks of neurons. Researchers typically simulate the artificial neurons and their interconnections using an ordinary digital computer—just as an engineer may use a computer to simulate an aircraft wing or a weather analyst to simulate a storm system. Connectionism came to the fore in the mid-1980s, when a group based at the University of California at San Diego reported some striking experiments. In one, an artificial neural network learned to form the past tenses of English verbs.[115] The network learned to respond correctly even to irregular verbs not previously encountered, such as 'weep' (wept) and 'cling' (clung)! The term 'connectionism' highlights the fact that what an artificial neural network learns is stored in its pattern of *inter-neural connections*.

Turing's unorganised computing machines had been forgotten until we published our paper 'On Alan Turing's Anticipation of Connectionism' in 1996,[116] and then in 1999 an article in *Scientific American* on Turing's forgotten ideas on neural computation.[117] Turing



The Turing test[34]

Judge:	In the first line of your sonnet which reads 'Shall I compare thee to a summer's day', would not 'a spring day' do as well or better?
Computer:	It wouldn't scan.
Judge:	How about 'a winter's day'? That would scan all right.
Computer:	Yes, but nobody wants to be compared to a winter's day.
Judge:	Would you say Mr. Pickwick reminded you of Christmas?
Computer:	In a way.
Judge:	Yet Christmas is a winter's day, and I do not think Mr Pickwick would mind the comparison.
Computer:	I don't think you're serious. By a winter's day one means a typical winter's day, rather than a special one like Christmas.

Passing the Turing test: Turing's sample dialogue (from 'Computing Machinery and Intelligence') described three types of unorganised machine. His *A-type* and ***B-type*** unorganised machines consist of randomly connected two-state 'neurons' whose operation is synchronised by means of a central digital clock; we call these 'Turing Nets'. It is Turing's discussion of B-types that anticipates modern connectionism. Turing's *P-type* unorganised machines are not neuron-like but are modified Turing machines: they have, Turing said, 'two interfering inputs, one for "pleasure" or "reward" ... and the other for "pain" or "punishment"'.[118] Turing studied P-types in the hope of discovering procedures for 'training' a machine to carry out a task. It is a P-type machine that Turing was speaking of when, in the course of his famous discussion of strategies for building machines to pass the Turing test, he said 'I have done some experiments with one such child-machine, and succeeded in teaching it a few things'.[119]

B-types too can be taught, and the most significant aspect of Turing's discussion of B-types is undoubtedly his idea that an initially random network can learn to perform a specified task by means of what he described as 'interfering training'[120]:

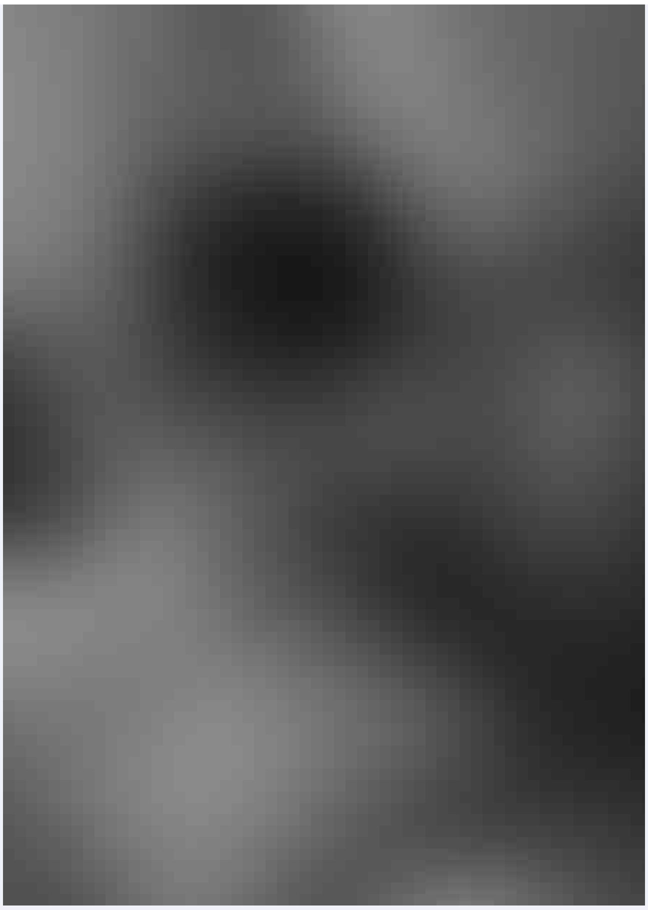
> **Many unorganised machines have configurations such that if once that configuration is reached, and if the interference thereafter is appropriately restricted, the machine behaves as one organised for some definite purpose.**[121]

In a B-type, the training process renders certain neural pathways effective and others ineffective—training hones the network for a specific task by selectively disabling and enabling connections.

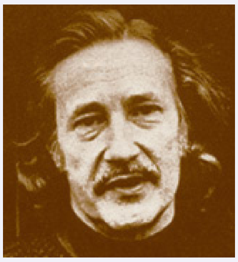
Turing theorized that 'the cortex of the infant is an unorganised machine, which can be organised by suitable interfering training', and he described A-type unorganised machines as 'about the simplest model of a nervous system with a random arrangement of neurons'.[122] He found 'this picture of the cortex as an unorganised machine ... very satisfactory from the point of view of evolution and genetics'.[123] Turing had no doubts concerning the significance of his unorganised machines. Of Turing Nets, he said

> **[M]achines of this character can behave in a very complicated manner when the number of units is large ... It would therefore be of very great interest to find out something about their behaviour.**[124]

In its treatment of learning, Turing's 'Intelligent Machinery' goes importantly beyond the famous 1943 paper on neural networks by McCulloch and Pitts.[125] McCulloch and Pitts gave only a perfunctory discussion of learning, saying no more than that the mechanisms supposedly underlying learning in the brain—they specifically mentioned the formation of new inter-neural connections and changes in the 'threshold' at which a neuron 'fires'—can be mimicked by means of nets whose connections and thresholds are *fixed*.[126] Turing's idea of using supervised interference to train an initially random arrangement of neurons is nowhere prefigured. It is also noteworthy that McCulloch stressed the extent to which his and Pitts' 1943 paper on neural networks is indebted to Turing's 1936 paper 'On Computable Numbers'. McCulloch said in 1948: 'I started at entirely the wrong angle ... and it was not until I saw Turing's paper that I began to get going the right way around, and with Pitts' help formulated the required logical calculus. What we thought we were doing (and I think we succeeded fairly well) was treating the brain as a Turing machine.'[127]



Dietrich Prinz playing the Ferranti Mark I computer. Prinz wrote the first chess program to be implemented.[35]

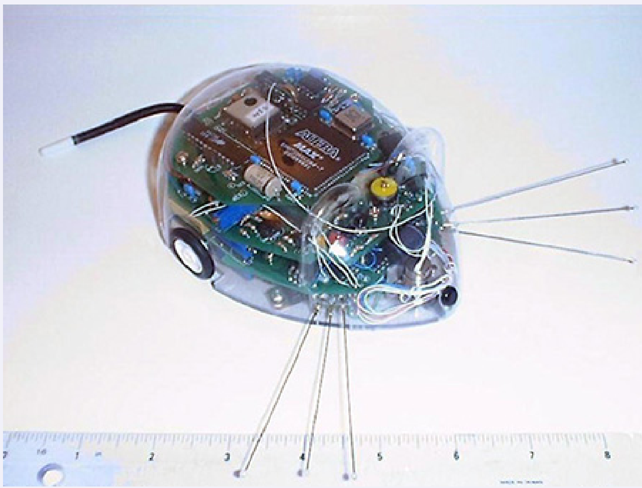


Strachey[31]

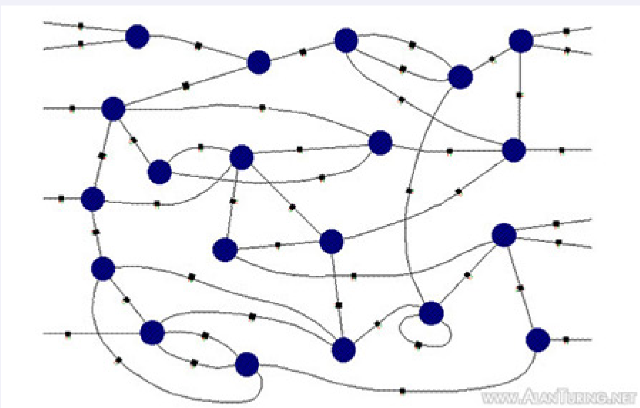
Turing also envisaged the procedure—nowadays used extensively by connectionists—of programming training algorithms into a computer simulation of an unorganised machine. In modern connectionism, repeated applications of a training algorithm (such as the ***backprop*** or 'back propagation' algorithm) cause the required pattern of connectivity to develop gradually within the network during the training phase. Turing had no algorithm for training his B-types, however. He saw the development of training algorithms for unorganised machines as a central problem. With characteristic farsightedness Turing ended his discussion of unorganised machines by sketching the research programme that connectionists are now pursuing:

> **I feel that more should be done on these lines. I would like to investigate other types of unorganised machines ... When some electronic machines are in actual operation I hope that they will make this more feasible. It should be easy to make a model of any particular machine that one wishes to work on within such a UPCM [universal practical computing machine] instead of having to work with a paper machine as at present. If also one decided on quite definite 'teaching policies' these could also be programmed into the machine. One would then allow the whole system to run for an appreciable period, and then break in as a kind of 'inspector of schools' and see what progress had been made.**[128]

Tony Oettinger in the courtyard of Clare College, Cambridge. Oettinger wrote the first learning programs.[36]



A P-type unorganised machine embodied in a robot. This P-type machine rodent was built in 2000 by Ovi Chris Rouly at New Mexico State University. More details can be found at **http://www.maelzel.com/Programs/ DARYL/R_Model.htm**. © Ovi Chris Rouly



Fragment of a large Turing Net[37]

Turing was unable to pursue his research into unorganised machines very far. At the time, the only electronic stored-program computer in existence was the tiny **Manchester Baby**. By the time Turing had access to the **Ferranti Mark I**, in 1951, his interests had shifted and he devoted his time to modelling biological growth. At the National Physical Laboratory, Turing's ideas on learning were pursued by his colleagues **Donald Davies** and **Michael Woodger**. Their Cybernetic Model, constructed in 1949, was a hardware simulation of six Boolean neurons.[129] In a demonstration on BBC TV in 1950, the Cybernetic Model mimicked simple learning in an octopus.

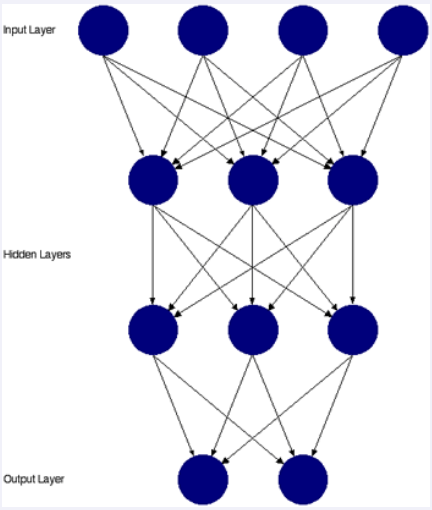
In the year of Turing's death (1954) two researchers at MIT, Wesley Clark and Belmont Farley, succeeded in running the first computer simulations of neural networks.[130] Clark and Farley were unaware of Turing's earlier work and their neural architecture was quite different from his: Clark and Farley used **'weighted' connections** between neurons, as is now usual in connectionism. Clark and Farley were able to train their networks—which contained a maximum of 128 neurons —to recognise simple patterns. In addition, they discovered that the random destruction of up to 10% of the neurons in a trained network does not affect the network's performance at its task—a feature reminiscent of the brain's ability to tolerate damage.

The work begun by Clark and Farley was developed very considerably by Frank Rosenblatt at Cornell University, who built neural network-like computers that he called 'Perceptrons'.[131] Rosenblatt used the term 'connectionist' for the approach and his 1962 book *Principles of Neurodynamics* became the reference work for the emerging field. Modern connectionists regard Rosenblatt as the founding father of their approach, and it is still not widely realised that Turing wrote a blueprint for much of the connectionist project as early as 1948.

10. Turing and Artificial Life (A-Life)

In his final years Turing worked on (what since 1987 is called) Artificial Life (A-Life). The central aim of Artificial Life is a theoretical understanding of naturally-occurring biological life—in particular of the most conspicuous feature of living matter, its ability to self-organise (i.e. to develop form and structure spontaneously). A-Life characteristically makes use of computers to simulate living and life-like systems. Christopher Langton, who coined the term 'Artificial Life', wrote

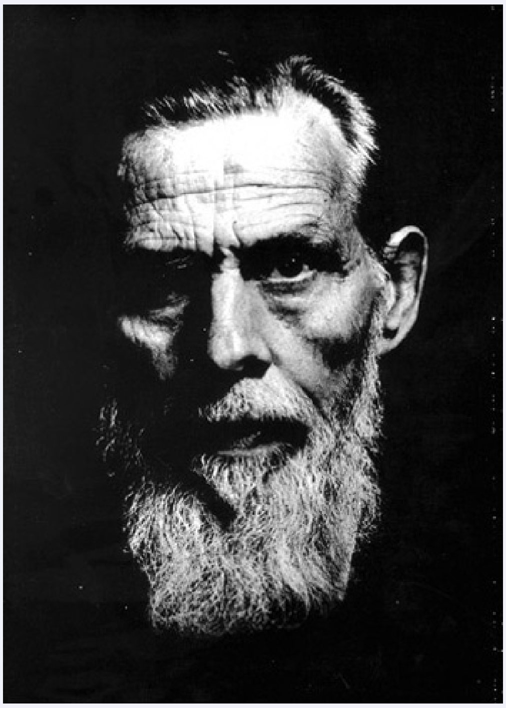
> **Computers should be thought of as an important laboratory tool for the study of life, substituting for the array of incubators, culture dishes, microscopes, electrophoretic gels, pipettes, centrifuges, and other assorted wet-lab paraphernalia, one simple-to-master piece of experimental equipment.**[132]



A modern connectionist network

Turing was the first to use computer simulation to investigate a theory of 'morphogenesis'—the development of organisation and pattern in living things.[133] He began this investigation as soon as the first **Ferranti Mark I** to be produced was installed at Manchester University. In February 1951 Turing wrote:

> **Our new machine is to start arriving on Monday. I am hoping as one of the first jobs to do something about 'chemical embryology'. In particular I think one can account for the appearance of Fibonacci numbers in connection with fir-cones.**[134]


Warren McCulloch[38]

Shortly before the Ferranti computer arrived, Turing wrote about his work on morphogenesis in a letter to the biologist J. Z. Young. The letter connects Turing's work on morphogenesis with his interest in neural networks, and to some extent explains why he did not follow up his suggestion in 'Intelligent Machinery' and use the Ferranti computer to simulate his unorganised machines.

> **I am afraid I am very far from the stage where I feel inclined to start asking any anatomical questions [about the brain]. According to my notions of how to set about it that will not occur until quite a late stage when I have a fairly definite theory about how things are done.**
>
> **At present I am not working on the problem at all, but on my mathematical theory of embryology ... This is yielding to treatment, and it will so far as I can see, give satisfactory explanations of-**
>
> **i) Gastrulation.**
>
> **ii) Polyogonally symmetrical structures, e.g., starfish, flowers.**
>
> **iii) Leaf arrangement, in particular the way the Fibonacci series (0, 1, 1, 2, 3, 5, 8, 13, ...) comes to be involved.**
>
> **iv) Colour patterns on animals, e.g., stripes, spots and dappling.**
>
> **v) Patterns on nearly spherical structures such as some Radiolaria, but this is more difficult and doubtful.**

> I am really doing this now because it is yielding more easily to treatment. I think it is not altogether unconnected with the other problem. The brain structure has to be one which can be achieved by the genetical embryological mechanism, and I hope that this theory that I am now working on may make clearer what restrictions this really implies. What you tell me about growth of neurons under stimulation is very interesting in this connection. It suggests means by which the neurons might be made to grow so as to form a particular circuit, rather than to reach a particular place.[135]

In June 1954, while in the midst of this groundbreaking work, Turing died. He left a large pile of handwritten notes concerning morphogenesis, and some programs.[136] This material is still not fully understood.

11. The Manchester Computer[137]

Turing and the NPL lost the race to build the world's first stored-program electronic digital computer—an honour that went to the University of Manchester, where the 'Manchester Baby' ran its first program on 21 June 1948. As its name implies, the Baby was a very small computer, and the news that it had run what was only a tiny program—just 17 instructions long—for a mathematically trivial task was (in Woodger's words) 'greeted with hilarity' by Turing's group.[138]

The Manchester computer project was the brainchild of Turing's friend and colleague Max Newman, whose section at Britain's wartime codebreaking headquarters, Bletchley Park, had contained 10 Colossus computers working around the clock to break German codes.[139] Newman, like von Neumann in the United States, was profoundly influenced by Turing's pre-war conception of a universal computing machine. It was in Newman's Computing Machine Laboratory that the Baby—the first real-world universal Turing machine—came to life.[140]

It was no coincidence that as soon as the war ended Turing and Newman both embarked on projects to create a universal Turing machine in hardware. Even in the midst of the attack on **Tunny**, Newman was thinking about the universal Turing machine. When **Flowers** was designing Colossus, Newman showed him Turing's 1936 paper about the universal machine ('On Computable Numbers'), with its key idea of storing symbolically-encoded instructions in memory.[141] By 1944 Newman was looking forward to setting up his own electronic computer project as soon as the war was over. As he said in a letter to von Neumann (quoted in chapter 2 **Codebreaking in World War II**), it was just a question of waiting until he 'got out' of Bletchley Park.[142]

Moreover, it had been Newman who, in a lecture in Cambridge in 1935, had launched Turing on the research that led to the universal Turing machine. In the lecture, Newman had defined a constructive process as one that a machine can carry out. He explained in an interview

> I believe it all started because [Turing] attended a lecture of mine on foundations of mathematics and logic ... I think I said in

Walter Pitts[39]

Pioneer of connectionism Frank Rosenblatt, with the image sensor (left) of the Mark I Perceptron[40]

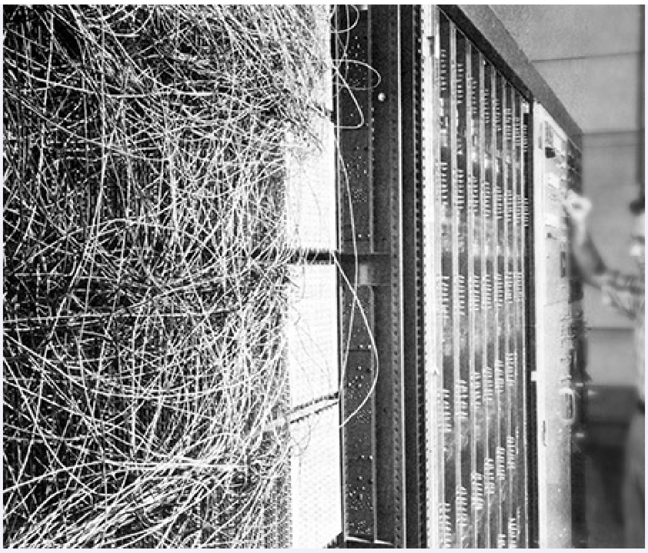
> the course of this lecture that what is meant by saying that [a] process is constructive is that it's a purely mechanical machine — and I may even have said, a machine can do it.
>
> And this of course led [Turing] to the next challenge, what sort of machine, and this inspired him to try and say what one would mean by a perfectly general computing machine.[143]

After Newman learned of Turing's universal computing machine early in 1936, he developed an interest in computing machinery which he described as being at that time 'rather theoretical'.[144] Turing himself was interested right from the start in building a universal computing machine[145], but he knew of no suitable technology. It was not until his and Newman's Bletchley days that the dream of building a miraculously fast all-purpose *electronic* computer took hold of them.

Historians who did not know of Colossus tended to assume that Turing and Newman inherited their vision of large-scale electronic computing machinery from the **ENIAC** group in the U.S. In reality, Colossus was the link between Turing's pre-war work and his and Newman's post-war projects to build an electronic stored-program computer. (Flowers saw the ENIAC just after the war. In his opinion the ENIAC was just a number cruncher—Colossus, with its elaborate facilities for logical operations, was 'much more of a computer than ENIAC', he said.[146])

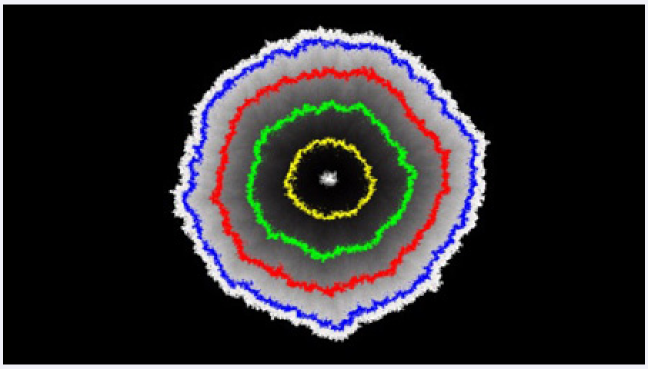
Newman had laid plans for his Computing Machine Laboratory following his appointment to the Fielden Chair of Mathematics at Manchester in September 1945. His formidable talent as an organiser, honed in the Newmanry, was now brought to bear on the problem of designing and constructing an electronic stored-program computer. Newman applied to the Royal Society for a sizeable grant (approved in May 1946[147]) to develop such a machine. Parts of the Colossi were transferred from Bletchley Park to Manchester, including some of the electronic panels—although not before every indication of their original purpose had been removed![148] The first work on the Baby computer made use of the 'bedstead' from a Colossus, the giant iron frame (right) that held the message tape.[149] 'It reminds me of Adam's rib', said **Jack Good**, one of the Newmanry codebreakers who moved with Newman to Manchester.[150]

At Bletchley, Newman had been chief executive of a project with a staff of over 300. He initiated and oversaw the creation of a dazzling array of machines, all lying at the frontier of current technology (not only the **Robinsons** and the Colossi—for descriptions of other Newmanry machines, see ***General Report on Tunny*** and ***Colossus: The Secrets of Bletchley Park's Codebreaking Computers***). Newman, himself no engineer, achieved these outstanding successes by the skilful use of a simple principle: get the right engineers involved, explain to them what needs to be done, and let them get on with it. (Once Newman had 'placed his trust in people he cut them loose to manage according to their own judgement' said Donald Michie, Newman's assistant at Bletchley Park.[151]) Not surprisingly, Newman followed the same method at Manchester. He educated Frederic Williams—who was recruited to Manchester University from the **Telecommunications Research Establishment** (TRE)—in the fundamentals of the stored-program computer.[152] At TRE during the war Williams and his assistant Tom Kilburn had worked on radar and were experts in electronic circuit design.[153] (They themselves knew nothing of Colossus. Williams did not hear about what had gone on at



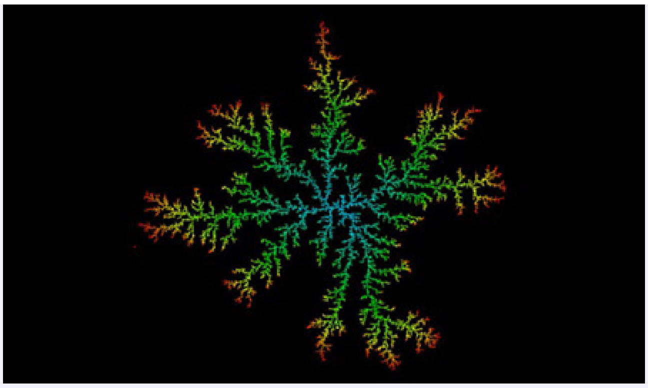
The Mark I Perceptron[41]

Pigmentation pattern in a seashell, generated by a modern variant of Turing's morphogenesis process. (A modification of Turing's 1952 reaction-diffusion process by H. Meinhardt.) **algorithmicbotany.org**[42]



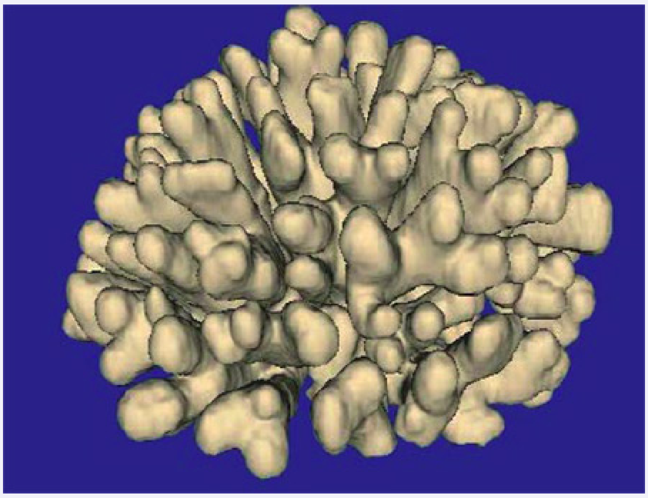
Pattern of growth on a flat surface, generated by M. Eden's variant of Turing's reaction-diffusion process. **algorithmicbotany.org**[43]

Bletchley until 'we were actually active in the computer field, when they thought they had something to gain from us'.[154] This was in 1952, when Williams was consulted by GCHQ and was invited to their headquarters, which by then had shifted from Bletchley Park to Eastcote near London.[155])



Pattern of growth produced by *diffusion-limited aggregation* (DLA), another variant of Turing's reaction-diffusion. **algorithmicbotany.org**[44]

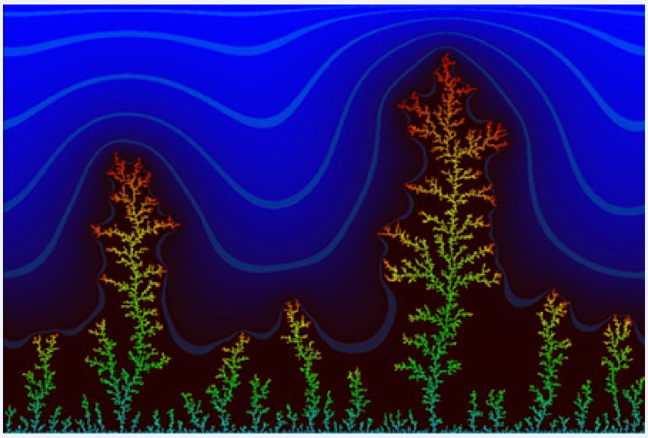
At the time he left TRE for Manchester in 1946, Williams was in the process of developing a method for storing patterns of zeros and ones on the face of a cathode ray tube—an idea that, with Kilburn's help, was rapidly to lead to the type of high-speed random access memory (RAM) known as the Williams Tube. (Although, since Williams and Kilburn shared the later patents and shared the royalties equally,[156] the name 'Williams-Kilburn Tube' would be more appropriate.[157]) The Williams Tube was a mainstay of early computing. Computers using Williams Tube memory included not only those built at the University of Manchester and by the Manchester engineering company Ferranti, but also the **SWAC** at the University of California at Los Angeles, the **Whirlwind I** at the Massachusetts Institute of Technology, the **IAS computer** at Princeton University, the **IBM 701**, TRE's own **TREAC** (Telecommunications Research Establishment Arithmetic[158] Computer) —and the ORDVAC, ORACLE, ILLIAC, MANIAC and other engagingly named computers.[159]



Sponge-like growth produced by DLA[45]

It was in the summer of 1946, at about the same time that the Royal Society approved Newman's grant, that Williams began his experiments at TRE on cathode ray tube storage.[160] Williams explained how it was that he came to be working on the problem of computer memory:

> **[O]nce [the German Armies] collapsed ... nobody was going to care a toss about radar, and people like me ... were going to be in the soup unless we found something else to do. And computers were in the air. Knowing absolutely nothing about them I latched onto the problem of storage and tackled that.**[161]



A forest of branching neuron-like structures produced by DLA. **algorithmicbotany.org**[46]

Newman learned of Williams' work. With his friend Patrick Blackett (Langworthy Professor of Physics at Manchester and one of the most powerful figures in the University[162]) Newman had a hand in the appointment of the 35-year-old Williams to the recently vacated Chair of Electro-Technics at Manchester. Both Newman and Blackett were members of the appointing committee.[163] Once appointed Williams secured Kilburn's secondment to his new department at Manchester.[164]

Williams had succeeded in storing a single binary digit in the autumn of 1946, a few weeks before he left TRE in December for the University of Manchester.[165] By this time Newman was already in possession of his Royal Society grant, but his **Computing Machine Laboratory** was little more than an empty room. 'So it was a very fruitful opportunity for collaboration', said Williams.[166] Williams' description of the Computing Machine Laboratory is vivid: 'It was one room in a Victorian building whose architectural features are best described as "late lavatorial". The walls were of brown glazed brick and the door was labelled "Magnetism Room"'.[167] Here Kilburn and Williams built the Manchester Baby. The first program, stored on the face of a Williams Tube as a pattern of dots, was inserted manually, digit by digit, using a panel of switches. 'A small electronic digital computing machine has been operating successfully for some weeks in the Royal Society Computing Machine Laboratory', wrote Williams and Kilburn in the letter to *Nature* announcing their success to the world.[168]

The regeneration principle

Turing had mentioned cathode ray tube storage on **page 48 of 'Proposed Electronic Calculator'**, saying that this was '[m]uch the most hopeful scheme' for storage. In effect Turing anticipated the Williams Tube in some detail, six months or more before Williams first heard of the problem of digital storage. Turing wrote:

> **It seems probable that a suitable storage system can be developed without involving any new types of tube, using in fact an ordinary cathode ray tube with tin-foil over the screen to act as a signal plate. It will be necessary to furbish up the charge pattern from time to time, as it will tend to become dissipated. ... If we were always scanning the pattern in a regular manner as in television this would raise no serious problems. As it is we shall have to provide fairly elaborate switching arrangements to be applied when we wish to take off a particular piece of information. It will be necessary to ... switch to the point from which the information required is to be taken, do some scanning there, replace the information removed by the scanning, and return to refurbishing from the point left off. ... None of this involves any fundamental difficulty, but no doubt it will take time to develop.**

'Furbishing up' (i.e. regenerating) the stored pattern was certainly the central problem. The pattern would persist for a time, but unless a means could be found to regenerate it, the stored information would eventually disappear. Moreover, scanning the stored pattern in order to read it also tended to destroy it.

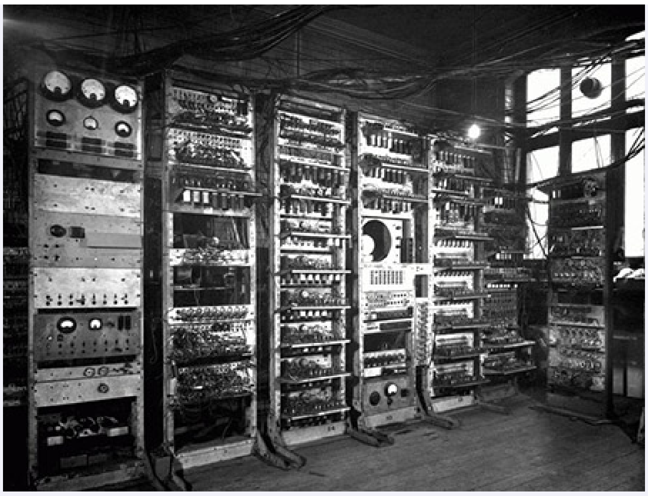
The earliest regenerative memories had used electrical capacitors as the storage units. At Bletchley Park during the war the codebreaking machine Aquarius was equipped with a regenerative memory consisting of a large bank of capacitors (details were not declassified until 2000).[169] Data read in from a punched paper tape was stored as a pattern of electrical charge, a charged capacitor representing the digit 1 and an uncharged capacitor 0. Since the charge would gradually leak away, the pattern was regenerated by means of a periodic pulse that topped up those capacitors already containing some charge—a contemporary account described the process of regeneration as proceeding 'according to the rule "to him that hath shall be given"'.[170] The memory could store in excess of 1500 binary digits (315 teleprinter characters expressed in 5-bit code). On the other side of the Atlantic, three or four years earlier, John **Atanasoff** had also built a capacitor-based regenerative memory capable of storing 1500 bits, for use in his largely unsuccessful 300-valve electronic calculator.[171]

The cathode ray tube, already in widespread use in the television industry and elsewhere, seemed in theory a better bet than the capacitor as the basis for a high-speed computer memory. Early unsuccessful experiments with cathode ray tube storage focussed, not on the ordinary type of tube recommended by Turing and later employed by Williams, but on a more complicated type of tube called an *iconoscope*. The iconoscope was a light-sensitive tube used in television cameras; it converted the optical image produced by the camera lens into electricity. When the light image fell on the outside

The Manchester 'Baby'. The world's first electronic stored-program computer, the Baby ran its first program in June 1948, in the Computing Machine Laboratory at the University of Manchester. Freddie Williams (right) and Tom Kilburn pose in front of the cathode ray display.[47]

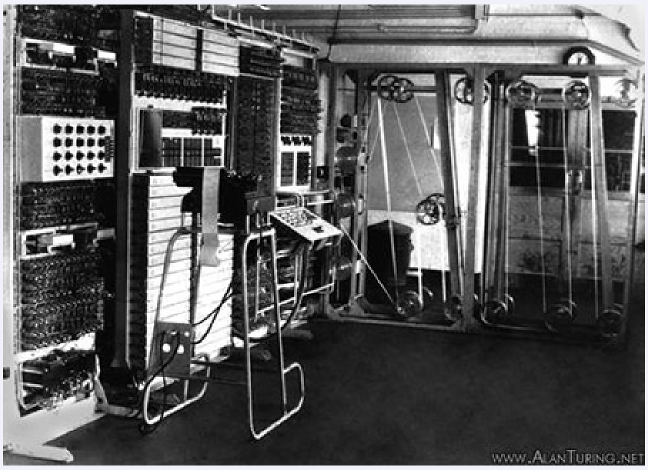
Max Newman. Head of the Tunny-breaking section called the 'Newmanry', Newman was in charge of the Colossi. He went on to found the Computing Machine Laboratory at Manchester University.[48]

surface of a plate (or 'mosaic') at the end of the iconoscope, a pattern of electrical charge was created; this pattern was read by a scanning beam of electrons inside the tube and converted into electrical current. Instead of using light, the early storage experiments placed a pattern on the iconoscope's plate by means of the electron beam that read the pattern once stored. These experiments were carried out at the Radiation Laboratory of the Massachusetts Institute of Technology, and the aim was to store, not digital information for use in electronic computers, but analogue information—lines and shapes—in connection with echo cancellation in radar. The plan was to store a radar trace and then 'subtract' it from subsequent traces, so enabling the operator to see only moving objects.



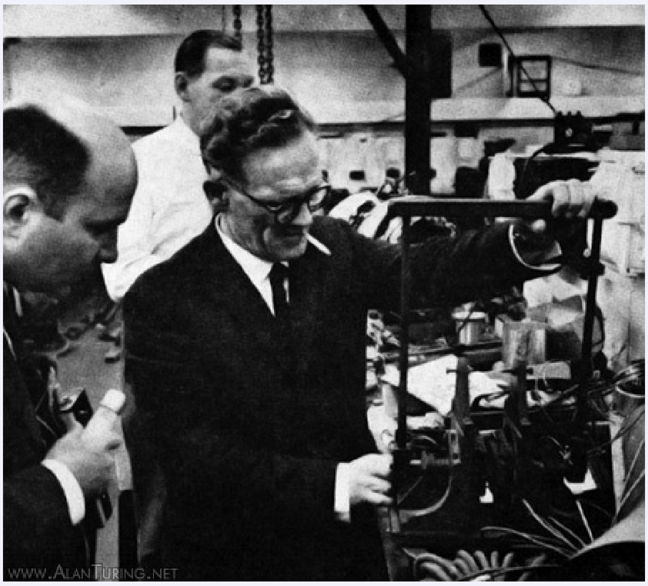
The Manchester computer[49]

The problem was that storage could not be achieved for more than very short periods. A Radiation Laboratory account dated February 1946 reported storage of a spiral pattern 'for nearly a second under suitable conditions'.[172] No satisfactory means was found of prolonging storage. Williams (a leading expert on radar) was shown the storage experiments during a visit to the Radiation Laboratory in June 1946. He later summed up what he saw there: 'You could put your signal on, and provided you went and looked for it again within half a second or so, there it was—but if you hoped to find it the next day, there it was gone.'[173]



Colossus X. In the foreground is the automatic typewriter for output. The large frame to the right (the 'bedstead') held two message tapes. As one job was being run, the tape for the next job would be loaded onto the bedstead, so saving time.[50]

Von Neumann had mentioned the iconoscope as a possible means of achieving high-speed *digital* storage in 'First Draft of a Report on the EDVAC' (1945).[174] He was aware of the need to regenerate the stored information and suggested what became known as the 'two-tube method'. Two iconoscopes were to be connected together and the stored information would be regenerated by means of continually passing it back and forth between the two tubes. Whether von Neumann learned of the possibility of using the iconoscope as a regenerative memory from Presper Eckert (engineering designer of the ENIAC and EDVAC), or whether perhaps Eckert learned of the idea from von Neumann, is unknown.[175] At any rate, Eckert lectured extensively on the possibilities of cathode ray tube storage at the Moore School in the summer of 1946.[176] **Kite Sharpless**, one of Eckert's team at the Moore School (and later director of the EDVAC project) had already experimented earlier that year with storing bits on the face of a standard cathode ray tube, using a metal foil placed over the screen as a target plate.[177] The basic set-up was very similar to that previously outlined by Turing. However, no method of regeneration was discovered and the experiments did not lead anywhere. The Moore School team was also interested in the two-tube method of regeneration,[178] but the difficulty was to make the method work in practice. At the MIT Radiation Lab attempts were made to store analogue traces using the two-tube method, but these too were unsuccessful.[179]



Freddie Williams[51]

At TRE Williams decided to tackle the problem of digital storage. He had seen the unsuccessful attempt at digital storage by Eckert's team at the Moore School, and during his visit to the Radiation Lab had also seen the two-tube experiment aimed at analogue storage. Kilburn explained:

> **What happened was that Freddie went to the States and he saw cathode ray tube attempts to store analogue signals. This was a two-tube system. Freddie came back and set [the experiment] up himself so that he could see what they were doing. So he set up this experiment of two tubes in which analogue signals were to be passed from one tube to**

another and vice versa, in order to regenerate analogue signals.[180]

Williams never managed to get the two-tube system to work, but during his efforts to adapt the two-tube system to digital storage he discovered the phenomenon that would make cathode ray tube storage a reality, the *anticipation pulse*. In the course of his attempt to store a straight line with a gap in it—effectively one bit—on the face of the cathode ray tube, Williams observed that when the electron beam was turned off at the start of the gap, an electrically charged 'marker' was naturally left on the screen.[181] The marker spread out a little over the screen and the result was that when the scanning beam returned to read the information on the screen, the marker provided advance warning of the point where the beam had turned off. This advance warning—the anticipation pulse—could be used to control the regeneration of the line-plus-gap, by turning the regenerating beam off at the point where the gap began. (The marker was an artefact of secondary electron emissions and the whole anticipation pulse effect was a quirk of the phosphorescent substance used to coat the face of the tube.) One off-the-shelf cathode ray tube was all that was required to make this method work, and Williams successfully stored one bit shortly after his discovery of the anticipation pulse.

A Williams Tube. The cathode ray tube is better known in its role of television tube.[52]

Bits stored on the face of a cathode ray tube[53]

In the end, the anticipation pulse was not used in the Baby computer. Kilburn soon discovered other methods of regeneration.[182] There was, in any case, a logical lesson to be learned from the anticipation pulse, as Williams remarked: 'although the anticipation pulse ... was the real breakthrough, as soon as you spotted that, you realised that you can reorganise operations ... you go and look at a spot and say "what's there?", all right that's there, so you put it back.'[183] The anticipation pulse was not needed.

Williams and Kilburn reflected in 1953 that 'it is amazing how long it took to realize the fact that if one can read a record once, then that is entirely sufficient for storage, provided that what is read can be immediately rewritten in its original position.'[184] Turing had realised this in 1945, and stated the idea very clearly in 'Proposed Electronic Calculator' (in the passage quoted earlier). Williams was sent a copy of 'Proposed Electronic Calculator' by the National Physical Laboratory in October 1946[185]—about the time of his discovery of the anticipation pulse (October or November 1946).[186] He need only have glanced at the table of contents of 'Proposed Electronic Calculator' in order to see the irresistible chapter title '**Alternative Forms of Storage**'.[187] Turing described the regeneration problem from a logician's point of view. His words ('It will be necessary to ... switch to the point from which the information required is to be taken, do some scanning there, [then] replace the information removed by the scanning …') might well have helped Williams towards an appreciation of the logical lesson that reading and rewriting are together sufficient to solve the problem of regeneration.

Setting the record straight

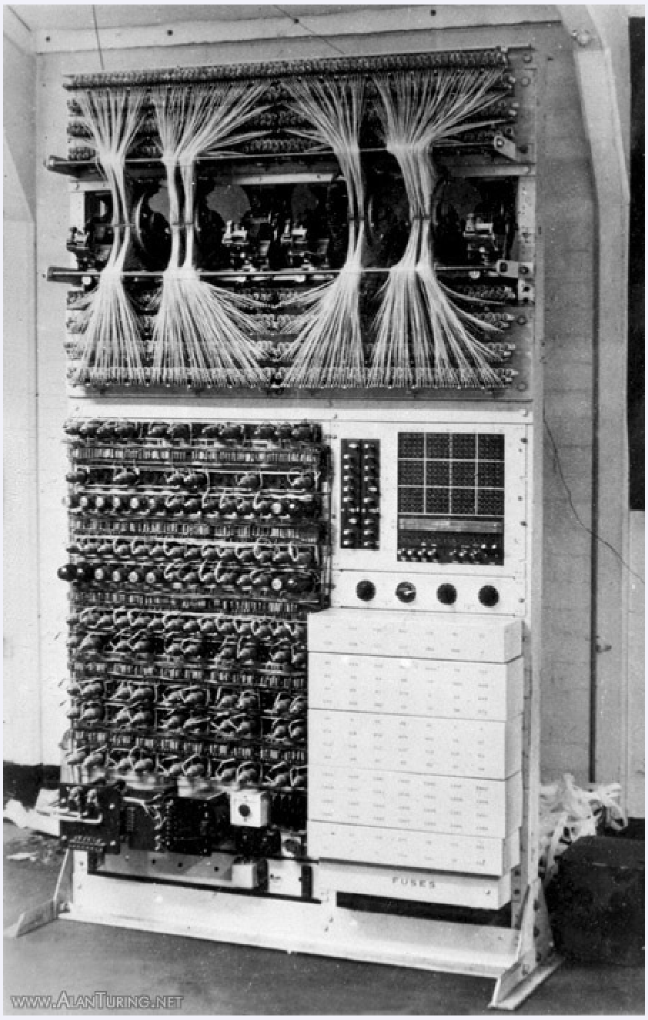
At the time of the Baby and its successor, the Manchester Mark I, Williams and Kilburn were given too little credit by the mathematicians at Manchester. Williams and Kilburn, who had translated the logico-mathematical idea of the stored-program computer into hardware, were regarded as excellent engineers but not as 'ideas men'.[188] Nowadays the tables have turned too far and the triumph at Manchester is usually credited to Williams and Kilburn alone. Fortunately the words of the late Freddie Williams survive to set the record straight:

> Now let's be clear before we go any further that neither Tom Kilburn nor I knew the first thing about computers when we arrived in Manchester University. We'd had enough explained to us to understand what the problem of storage was and what we wanted to store, and that we'd achieved, so the point now had been reached where we'd got to find out about computers. ... Newman had already got a grant from the Royal Society to build a computer but had not in fact yet embarked on the problem of building it. Nor indeed was Newman, who was a mathematician, the right sort of person to build a computer. So it was a very fruitful opportunity for collaboration between the maths department and the electrical engineering department — and Newman explained the whole business of how a computer works to us. ... [The building of the Baby computer] was a straightforward process: we had the method of storage; we had instructions from Newman as to what facilities needed to be provided.[189]

Turing[54]

Historians have either ignored or underestimated the roles played by Turing and Newman in the development of the stored-program computer at Manchester.[190] Even Newman's own account of the matter is—characteristically—self-effacing.[191] Williams, however, is perfectly clear in attributing credit:

> Tom Kilburn and I knew nothing about computers ... Professor Newman and Mr A. M. Turing ... knew a lot about computers ... They took us by the hand and explained how numbers could live in houses with addresses ...[192]



Aquarius. 'This form of memory is similar to random access storage on the screen of a cathode ray tube, as in the Williams tube memory', says Harry Fensom, one of the creators of Aquarius.[55]

Going by Williams' later description (quoted **below**), Newman's explanation of the stored-program computer to Williams and Kilburn—which took place early in 1947—resembled an account that he gave in an address to the Royal Society on 4 March 1948 and which was captured in print:

> In modern times the idea of a universal calculating machine was independently [of Babbage] introduced by Turing ... There is provision for storing numbers, say in the scale of 2, so that each number appears as a row of, say, forty 0's and 1's in certain places or 'houses' in the machine. ... Certain of these numbers, or 'words' are read, one after another, as orders. In one possible type of machine an order consists of four numbers, for example 11, 13, 27, 4. The number 4 signifies 'add', and when control shifts to this word the 'houses' *H*11 and *H*13 will be connected to the adder as inputs, and *H*27 as output. The numbers stored in *H*11 and *H*13 pass through the adder, are added, and the sum is passed on to *H*27. The control then shifts to the next order. In most real machines the process just described would be done by three separate orders, the first bringing ‹*H*11› (=

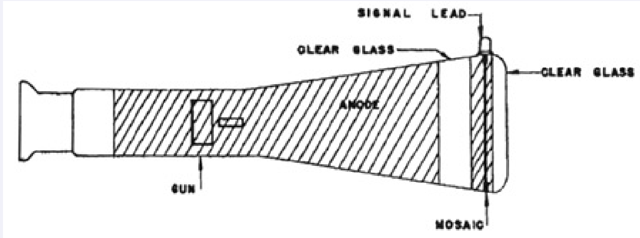
> **content of *H*11) to a central accumulator, the second adding ‹*H*13› into the accumulator, and the third sending the result to *H*27; thus only one address would be required in each order. ... A machine with storage, with this automatic-telephone-exchange arrangement and with the necessary adders, subtractors and so on, is, in a sense, already a universal machine ...**[193]

Here Newman's explanation presents both Turing's three-address format for instructions (source 1, source 2, destination, operation)[194] and also a single-address format (address, operation) associated with a central 'accumulator'. (An accumulator is a storage unit able to form the sum of an incoming number and the number already stored; this sum then replaces the previous content of the store.) Newman's mention of the single-address format and a central accumulator was a reference to the centralised design championed by von Neumann in 'First Draft of a Report on the EDVAC' (1945) and 'Preliminary Discussion of the Logical Design of an Electronic Computing Instrument' (1946)[195] (see further chapter 12 **The Manchester Computer and John von Neumann**). The three-address format was introduced by Turing in Versions VI and VII of the ACE design (see 'The Turing–Wilkinson Lecture Series' in *Alan Turing's Automatic Computing Engine*). From Turing's point of view, its use enabled one instruction to replace three single-address instructions, so giving greater speed.[196]

Newman went on to describe program storage ('the orders shall be in a series of houses *X*1, *X*2, ...') and conditional branching ('A *conditioned* change of control is needed, i.e. the capacity to change control to an arbitrarily specified order if (say) a certain number is positive, but to go on to the next order otherwise').[197] Newman said: 'The provision for change of control, and above all for conditional change of control according to the sign of a certain number, is the most characteristic part of these machines'.[198] Elsewhere he emphasised the connection with Colossus: Colossus 'had a very characteristic feature which is sometimes taken to be the characteristic of a general computing machine; and that is, that it looks at the answer to what is done so far and does one thing if the answer is 0, say, and another thing if the answer is 1, and this is a very important step—and this step was taken in Colossus'.[199]

In his Royal Society lecture Newman then summed up the essentials of a stored-program computer, probably in much the same words that he used when giving his 'few lectures' the previous year to the engineers:

> **From this highly simplified account it emerges that the essential internal parts of the machine are, first, a storage for numbers (which may also be orders). ... Secondly, adders, multipliers, etc. Thirdly, an 'automatic telephone exchange' for selecting 'houses', connecting them to the arithmetic organ, and writing the answers in other prescribed houses. Finally, means of moving control at any stage to any chosen order, if a certain condition is satisfied, otherwise passing to the next order in the normal sequence. Besides these there must be ways of setting up the machine at the outset, and extracting the final answer in**



An iconoscope[56]

MIT Radiation Lab[57]

F. C. Williams[58]

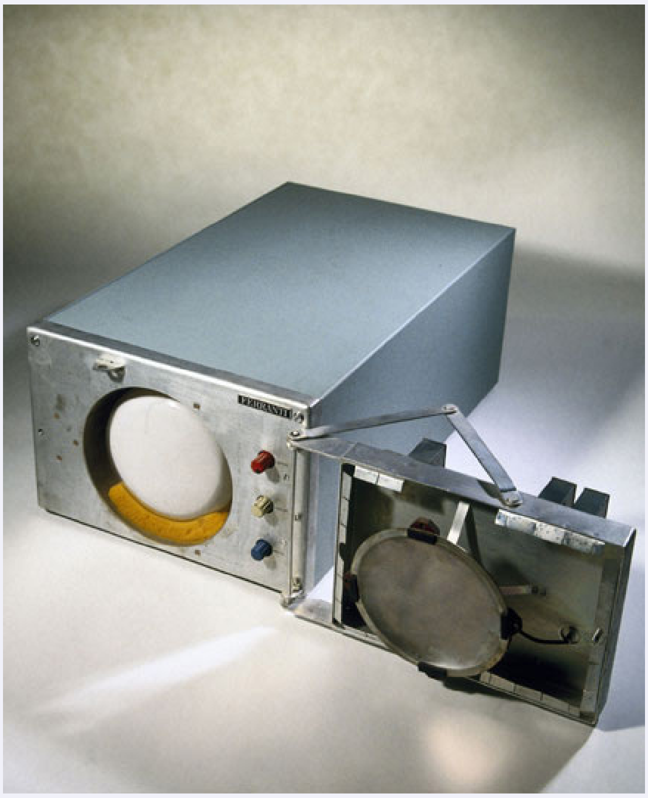
useable form.[200]

Newman had explained to the engineers what they needed to build.[201] And so (although this is not what orthodox histories of the Manchester computer maintain) credit for the Manchester computer—tellingly called the 'Newman–Williams machine' by Huskey in a report written shortly after his visit to the Manchester project in 1947[202]—belongs not only to Williams and Kilburn but also to Newman. It is also clear that the influence on Newman of Turing's 1936 paper, and of Flowers' Colossus, was crucial.[203] A separate thread of the story, Turing's influence on Kilburn, is disentangled below. Turing's contribution to the development of Kilburn's design for the first computer has not been recognised in orthodox histories of the Manchester project.

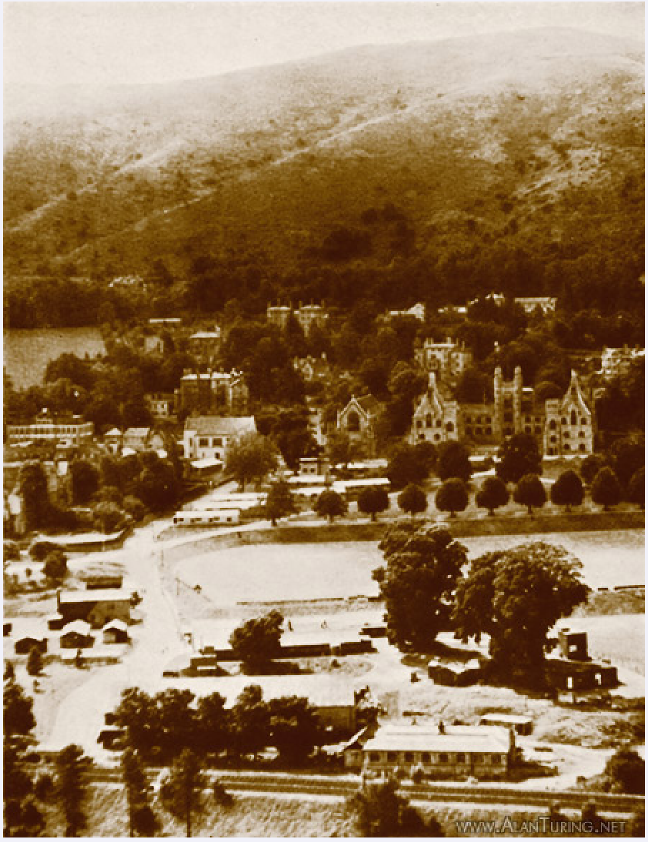
In a letter written in 1972, Williams described in some detail what he and Kilburn were told by Newman. Williams said that this was the 'first information' that he received about the organisation of computers, although (as we will explain) Kilburn had in fact already received a thorough grounding in the basics of computer design in lectures given by Turing in London. Williams said, accurately enough, that the Baby machine was an 'embodiment' of what he and Kilburn were told by Newman in the 'few lectures' that he gave them in 1947. Yet in its detailed twists and turns, the story of the coming into existence of the Baby is much more complicated than Williams' summary conveys:

> About the middle of the year [1946] the possibility of an appointment at Manchester University arose and I had a talk with Professor Newman who was already interested in the possibility of developing computers and had acquired a grant from the Royal Society of £30,000 for this purpose. Since he understood computers and I understood electronics the possibilities of fruitful collaboration were obvious. I remember Newman giving us a few lectures in which he outlined the organisation of a computer in terms of numbers being identified by the address of the house in which they were placed and in terms of numbers being transferred from this address, one at a time, to an accumulator where each entering number was added to what was already there. At any time the number in the accumulator could be transferred back to an assigned address in the store and the accumulator cleared for further use. The transfers were to be effected by a stored program in which a list of instructions was obeyed sequentially. Ordered progress through the list could be interrupted by a test instruction which examined the sign of the number in the accumulator. Thereafter operation started from a new point in the list of instructions. This was the first information I received about the organisation of computers. ... Our first computer [the Baby] was the simplest embodiment of these principles, with the sole difference that it used a subtracting rather than an adding accumulator.[204]

The use of subtraction as the basic arithmetical operation was a clever



A Williams Tube in its case. The pickup plate is visible inside the lid of the case.[59]



TRE (Telecommunications Research Establishment) in Malvern, where Williams achieved his breakthrough[60] idea that simplified the logical design of the Baby computer. In an interview Williams explained why subtraction was chosen:

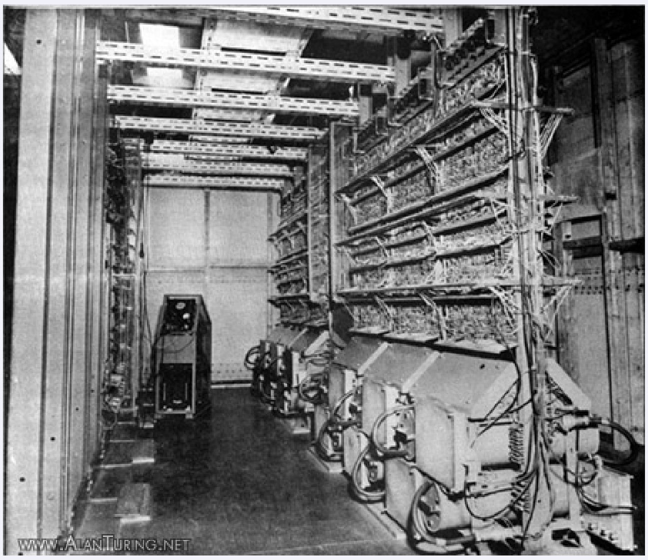
> **The facilities we decided to provide were the absolute minimum. For example, the only arithmetic operation we were able to perform was subtraction, because you can do addition by means of subtraction because you can subtract something from nothing and get its negative, and then subtract its negative from what you want to add it to, and you get the sum — and you can't do the opposite of this, you can't do anything by addition other than addition. So we had the one basic arithmetic operation, subtraction, and the other important thing that we had was the facility to take one of two paths through the programme according to the sign of the number standing in the accumulator. This is the basic thing about computers that makes them universal. So in all we had about five possible instructions that the machine could obey.**[205]

Williams[61]

Williams[62]

The detailed design of the Baby was largely done by Kilburn. 'I designed the smallest computer which was a true computer (that is a stored program computer) which I could devise', Kilburn said.[206] It was Kilburn, too, who contributed the idea of basing the design around the single arithmetical operation of subtraction; when asked (by Copeland) whose idea this was, Kilburn replied simply 'Mine!'.[207]

Nevertheless, the fundamental architectural ideas embodied in the Baby were neither Kilburn's nor Williams'.



Interior view of the TRE computer TREAC.[63] TREAC contained a Williams Tube memory.

Turing's influence on Kilburn

Turing's early input to the developments at Manchester, hinted at by Williams in his above-quoted reference to Turing, was via the lectures on computer design that Turing and his assistant Wilkinson gave in London during the period December 1946 to February 1947 (the lecture notes are in *Alan Turing's Automatic Computing Engine*).[208] The lectures were held between 2 p.m. and 5 p.m. on successive Thursday afternoons in a rather dingy underground room at the Headquarters of the Ministry of Supply, then housed in the Adelphi Hotel, Baker Street, London.[209] The series of nine lectures covered Versions V, VI, and VII of Turing's design for the ACE. Representatives attended from various organisations that planned to use or build an electronic computer. Among the audience was Kilburn.[210] Turing's lectures—which occurred several months before the lectures that Newman gave Williams and Kilburn at Manchester—played a key role in introducing Kilburn to the fundamentals of computer design.

Kilburn usually said, when asked where he got his basic knowledge of the computer from, that he could not remember[211]; for example, in a 1992 interview he said, 'Between early 1945 and early 1947, in that period, somehow or other I knew what a digital computer was ... Where I got this knowledge from I've no idea'.[212] However, in his first report on the Manchester computer work, dated 1947, Kilburn referred to 'unpublished work' by Turing—and used various of Turing's technical terms.[213] (These included 'table of instructions' and 'universal machine', and also various terms that, whether or not they originated with Turing, were distinctive of Turing's 1946-7 lectures—for example, 'source', 'destination', 'temporary store', 'staticiser', and 'dynamiciser'.) In a subsequent report written when the computer was working, Kilburn said 'I wish to acknowledge my indebtedness to Prof. M. H. A. Newman, and Mr. A. M. Turing for much helpful discussion of the mathematical requirements of digital computing machines'.[214] Williams summed up Turing's role in this way: Turing was 'instrumental, with Newman, in instructing us in the basic principles of computing machines, not on the engineering side of course, on the mathematical, and we had very close collaboration with both of them'.[215]

Turing's influence on the evolution of Kilburn's design for the Baby machine was in fact considerable. In December 1947 Kilburn described a 'hypothetical' machine, in a report to TRE dated 1 December. The hypothetical machine, he said, had 'the sole purpose of demonstrating the function of the storage system'.[216] In Kilburn's hypothetical machine, each of the machine's elementary arithmetical and logical operations is implemented by a separate hardware unit or 'destination'; each of these units is numbered and the numbers are referred to by Kilburn as 'destination numbers'.[217] Each instruction, Kilburn explained, transferred a number 'from one part of the machine—a "source"—to another—a "destination"'. An instruction consisted of two numbers, a source number *s* and a destination number *d*, which control a source tree and a destination tree respectively. In Kilburn's design, as in Version V of the ACE, instructions contained no 'operation code' (an operation code is the code-name of a operation, for example addition). The operation that was to be performed was implied by the destination number. The source tree accesses the number with address *s* in the main memory, and the destination tree accesses the destination, which is to say accesses the unit that will perform the required operation, e.g. the adder. Each operand is routed from the main memory via the source tree to the destination tree. There was no central accumulator, and everything was very different from the centralised design being promulgated by von Neumann in the United States.

Newman as a young Fellow of St. John's College, Cambridge[64]

Concerning the provenance of his design, Kilburn said rather vaguely that the design 'contain[ed] the essential framework of proposed machines'.[218] In fact, the 'decentralised' structure that he proposed is extremely similar to Turing's design for the ACE.[219] In the ACE there was no central accumulator, but rather a collection of different destinations (delay lines) where the different operations were performed—addition, subtraction, test whether zero, and so forth. The explanation of how it was that by 1947 Kilburn 'somehow or other ... knew what a digital computer was' is no mystery: Turing taught him![220]

Newman in 1940, two years before he joined the codebreakers at Bletchley Park[65]

Here, in briefest outline, is the explanation that Kilburn received, during the 1946-7 lectures, of how to build a computer:

> **Transfer of numbers is achieved by indicating a SOURCE and a DESTINATION by the control system. ... Certain [delay] lines are used exclusively for certain purposes ... For example, lines 2 and 3 are always used for addition. ... In order that a combination of 10 signals ... may be used to tap any source or open any destination a system of inter-connection is arranged, which is known as a TREE. ... In Versions V and VI the Source and Destination trees control 1024 Sources and Destinations.**[221]

(For a complete description of the ACE's architecture and instruction formats see *Alan Turing's Automatic Computing Engine*, chapters 4, 9, 11 and 22.)

It is clear, then, that Turing supplied the central ideas leading to Kilburn's 1947 hypothetical machine: the basic design of the machine was that proposed by Turing for the ACE and described in Turing's 1946-7 lectures. In an interview Kilburn said dismissively that the 'only thing' he 'got from' Turing's lectures 'was an absolute certainty that my computer wasn't going to look like that'.[222] He did not explain, though, that he came to this decision only by designing a detailed hypothetical machine in the Turing mould!

Turing was Kilburn's mentor, but once Kilburn had learned all he neede, he went his own way, and his 1947 ACE-like design was in fact a dead end; it bore very little relation to the actual Baby. The Baby was a centralised machine (see **diagram**). Three cathode ray tubes (marked 'S', 'A', and 'C' in the diagram) formed the Store, Accumulator, and Control. All calculations were performed by transfers of numbers between the Store and the central Accumulator.[223]

Kilburn himself, in later life, was an important source of what has unfortunately become the canonical view of the roles of Turing and Newman—or rather their lack of role—in the origin of the Baby. Although in his first papers on the Manchester computer Kilburn gave credit to both Turing and Newman, in later years he was at pains to assert the independence of his and Williams' work from outside influence, presenting the history of the Baby in a way that assigned no role to Turing or to Newman. In an interview (with Copeland) in 1997, Kilburn emphasised that Newman 'contributed nothing to the first machine' (the Baby). Kilburn said: 'What I'm saying is that the origin is not Newman in any way whatsoever. I know it has been described by others as such—but it wasn't'. Turing's only contributions, Kilburn said, came after the computer was working, and included preparing a 'completely useless' programming manual.

Another claim in the orthodox history of computing is that the Manchester computer was a wholly and uniquely British achievement —the very first modern computer, conceived and built by Kilburn, Williams and a couple of lads, in the same city that had given birth to the first industrial revolution nearly two centuries previously. However, close study of the documentary evidence reveals the considerable extent to which the Baby was indebted to American ideas.

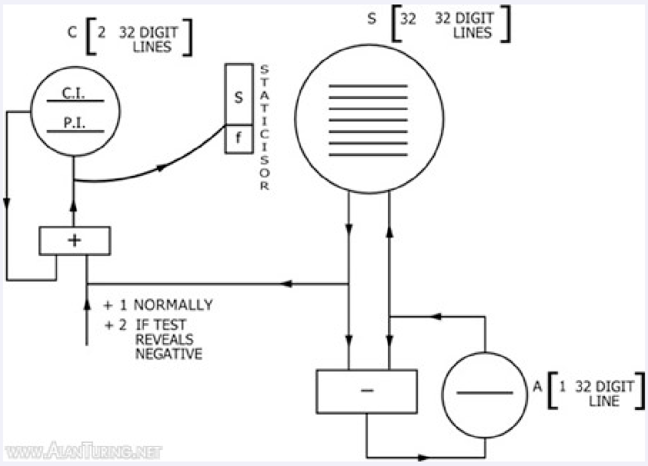
12. The Manchester Computer and John von Neumann

The 1957 American *Family Tree of Computer Design* (right) depicted the Manchester development as a slim branch sprouting from the strapping EDVAC trunk. However, the *Tree* also mistakenly portrayed the ACE as an outgrowth from the same sturdy trunk. Those who drew the tree in the late 1950s were blissfully ignorant of Colossus, and failed to recognise the other trunk on the opposite side of the Atlantic. Yet in the case of the Manchester computer, by a mixture of luck and jingoism the authors of the tree got the picture partly right.

The key question is: to what extent was the design of the Manchester Baby influenced by the thinking of von Neumann and his associates at the Moore School and Princeton? (Presper Eckert's role has already been touched upon in the sub-section **The regeneration principle**.[224] According to the Manchester engineers, the answer to this question is 'Not much, if at all'. Kilburn spoke scathingly of the von Neumann 'dictat'[225] and Geoff Tootill said:

Newman on a mountain in Wales, circa 1948[66]

The Manchester computer in Newman's Computing Machine Laboratory[67]



The Manchester 'Baby' computer[68]

As Williams and Kilburn described it, the basic rhythm of the Baby was 'four beats to the bar'.[196] The single-line store C.I. (for 'control instruction') holds the address at which the next instruction is stored in S. In the first beat, this address is transferred to the staticisor (in the Princeton idiolect, the staticisor was called the 'function table register'). The staticisor

> Williams, Kilburn and I (the three designers of the first Manchester machine) had all spent the 1939–1945 war at the Telecommunications Research Establishment doing R & D on radiolocation equipments. The main U.S. ideas that we accepted in return for our initiatives on these and later on computers were the terms 'radar' and 'memory' ... We disliked the latter term, incidentally, as encouraging the anthropomorphic concept of 'machines that think'.[226]
>
> To the best of my recollection FC [Williams], Tom [Kilburn] and I never discussed ... von Neumann's ... ideas during the development of the Small-Scale Experimental Machine [the Baby], nor did I have any knowledge of them when I designed the Ferranti Mk I. I don't think FC was influenced at all by von Neumann ... I think he was in general quite punctilious in acknowledging other people's ideas.[227]

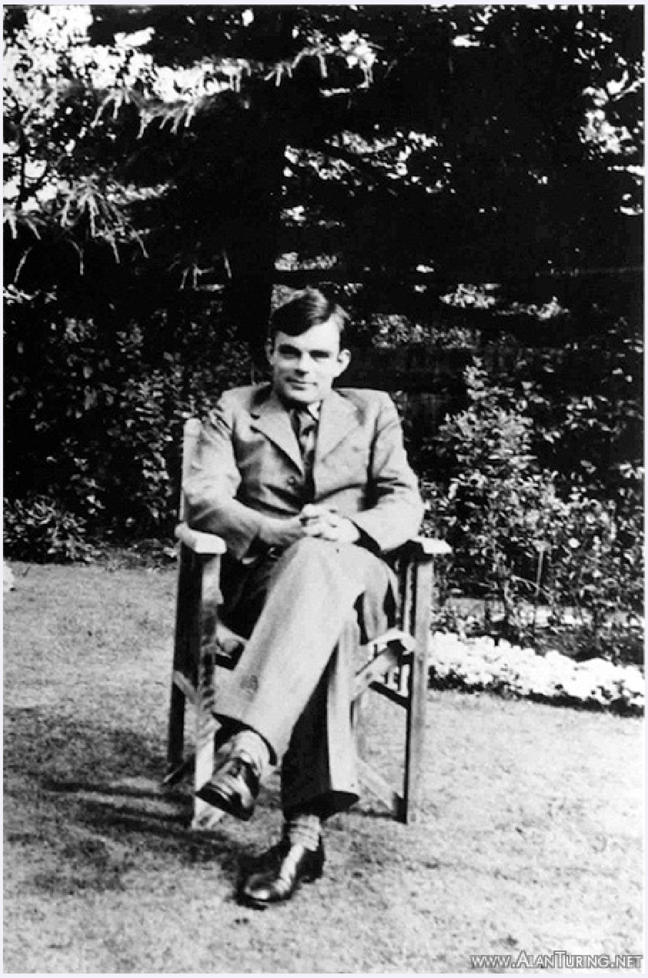
Williams himself, however, was aware that the thinking of the Manchester engineers might have been indirectly influenced by von Neumann. In a letter, after emphasising the fact that his first knowledge of computer design came from Newman, he remarked that the information 'may have derived from America through Newman'.[228]

Newman, like Turing, was well aware of von Neumann's 'First Draft of a Report on the EDVAC', and Newman did not share Turing's predilection for working alone from his own first principles. Newman was eager for all the fresh ideas about computers he could gather. In the summer of 1946 he and Jack Good visited Turing at the National Physical Laboratory for several days, in order to learn as much as they could about the design of the ACE.[229] Good was a leading cryptanalyst in the Newmanry and a co-designer of some of the equipment in Colossus II; in October 1945 Newman appointed him to the Manchester Mathematics Department. (Good tells his own story in his chapter 'From Hut 8 to the Newmanry' of *Colossus: The Secrets of Bletchley Park's Codebreaking Computers*.) Also in the summer of 1946 Newman sent David Rees, another ex-Newmanry mathematician with an interest in computers, to the Moore School lectures, where Eckert, Mauchly, and other members of the ENIAC–EDVAC group publicised their ideas on computer design.[230] In the autumn of 1946 Newman himself went to Princeton for three months.[231] Von Neumann's co-authored report 'Preliminary Discussion of the Logical Design of an Electronic Computing Instrument' (June 1946)[232] was studied closely at Manchester, although not by the engineers.

On his return to Manchester from Princeton, Newman gave two or three lectures on computer design to Williams and Kilburn (described **above**).[233] He covered the Princeton plans together with ideas of his own. Turing's lecture series had already provided Kilburn with a detailed and extended introduction to the state of the art; but Newman's emphasis on the use of a central accumulator must have opened Kilburn's eyes to the simplicity of a centralised design.

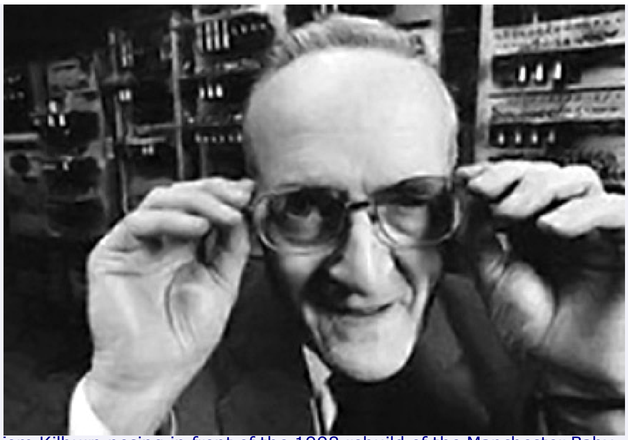
Newman's lectures inspired Good to write a few pages of notes expressing his first ideas on what the basic operations of a general-purpose computer should be.[234] These notes, which share notation with von Neumann's 'Preliminary Discussion' (e.g. 'CC' for conditional transfer of control, 'l' and 'r' for left and right shift, and 'R→A' for the

both controls the flow of information to and from the store, and controls the execution of the instructions in the program. Also in the first beat, 1 is added to the address in C.I., in preparation for the start of the next bar (or 2 is added if, in the next bar, the next instruction in the store is to be skipped). In the second beat, the staticisor selects the line of S designated by the address received from C.I., and routes the instruction which is stored there into the single-line store P.I. (for 'present instruction'). An instruction consists of a single address followed by a numerical code designating an operation (called the *function code*); and, correspondingly, the staticisor consists of two blocks of equipment, the s-block, which accesses the store S by means of an address (as just described), and the f-block, which causes the operation specified by the function code to be carried out. In the third beat, the present instruction is fed from P.I. back into the staticisor, so that in the next beat the s-block and f-block can do their work. In the fourth beat, the s-block accesses the number stored in the line of S whose address appears in the instruction, and the f-block causes the operation specified by the function code to be executed—e.g. the operation of subtracting the number in line *x* of S from the number in the accumulator and storing the result in the accumulator. After the fourth beat of the bar comes the first beat of the next bar. (The diagram indicates the potential for *adding* a number from S to the number stored in C.I., a facility not included in the original Baby but soon incorporated.)

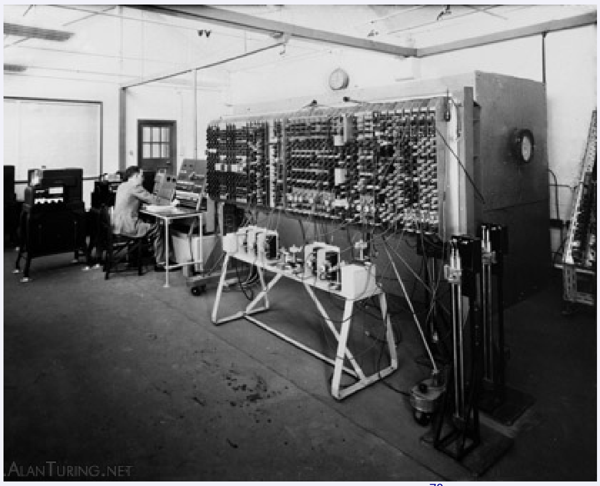


Turing[69]

operation of transferring the number in the accumulator A to the arithmetic register R), are a glorious mixture of ideas originating from Princeton, Newman, and Good himself.


'om Kilburn posing in front of the 1998 rebuild of the Manchester Baby Photo © Carolyn Djanogly.

In 1998, in his acceptance speech for the IEEE Computer Pioneer Award, Good announced that he had made a proposal for the Baby machine's basic instructions; the proposal was made 'at Kilburn's request', he said.[235] In May 1947 Good prepared an eight-page document for Kilburn, titled 'The Baby Machine'; this was written, he said, in response to a call from Kilburn 'for suggestions for a small number of basic instructions (or operations)'.[236] The 12 basic operations listed by Good were: (1) transfer the number in 'house' *x* (there were 64 'houses' or storage registers) to the accumulator *A*; (2) add the number in house *x* to the number in the accumulator and store the result in the accumulator; (3) transfer the negative of the number in house *x* to the accumulator; (4) subtract the number in house *x* from the number in the accumulator and store the result in the accumulator; (5) transfer the number in the accumulator to (arithmetic) register *R*; (6) transfer the number in *R* to the accumulator; (7) transfer the number in the accumulator to house *x*; (8) transfer the number in house *x* to *R*; (9) shift the number in the accumulator one place to the left; (10) shift the number in the accumulator one place to the right; (11) transfer control unconditionally to the instruction in house *x*; and (12) conditional transfer of control, viz transfer control to the instruction in house *x* if the number in the accumulator is greater than or equal to 0.[237] Good then gave some examples of programs for this baby machine, including multiplication of arbitrary numbers (between -2^{31} and 2^{31}) and testing the parity of a number.



The Pilot Model of Turing's ACE in 1952[70]

The set of basic operations that Good supplied to Kilburn was in fact nothing more than a simplification of the more complex set given in von Neumann's 'Preliminary Discussion of the Logical Design of an Electronic Computing Instrument'. Von Neumann had himself pointed out that the set of operations he listed could be simplified, saying 'many can be programmed by means of the others'.[238] (Of Good's 12 operations, only number (5)—transfer the number in *A* to *R*—was not in von Neumann's larger set.[239]) Good had injected Princeton ideas into Kilburn's thinking.

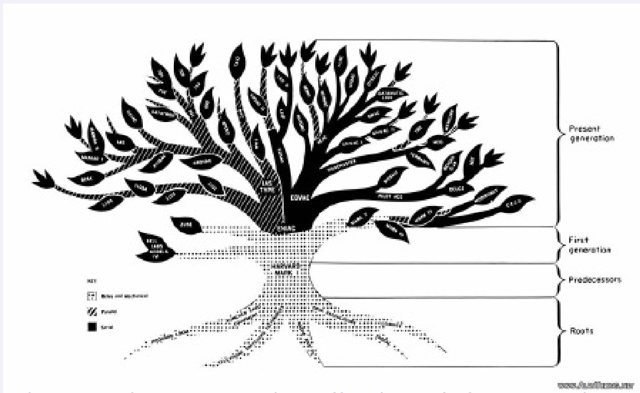
Kilburn's instruction set for the 1948 Baby was a subset of Good's May 1947 instruction set.[240] Kilburn reduced Good's set of 12 elementary operations to 5: (3), (4), (7), (11), a modified form of conditional transfer of control (skip the next instruction in the store if the number in the accumulator is less than 0), and a sixth operation, stop the machine.[241] Good's operations (1) and (2) were unnecessary for Kilburn's purposes, since subtraction was to be his only basic arithmetical operation. The two shift operations (9) and (10) were logically redundant, and could be dispensed with in a minimal machine (as Good noted, the left shift is just multiplication by 2, and the right shift is division by 2). Good's instructions (5), (6) and (8) were also unnecessary, since there was no arithmetic register *R* in the Baby.

Once Kilburn had had the idea that the only arithmetical operation should be subtraction, and had reduced Good's instruction set from 12 basic operations to 5, he knew what he needed to build: a minimal machine whose hardware components were the Store, Accumulator, and Control presupposed by Good's operations.[242]

Kilburn never acknowledged a debt to Good—let alone to von Neumann—but as he himself said, 'You can't start building until you have got an instruction code'.[243] Talking about the origin of the basic instructions in an interview with Copeland, Kilburn said that 'these instructions sort of write themselves'. He did not mention Good.[244] As to von Neumann, Kilburn listed 'Unpublished work, von Neumann, J.' among the references for his December 1947 report to TRE.[245] However Kilburn, and the other engineers working on the Baby, were almost certainly unaware of the true extent of their indebtedness to von Neumann. Kilburn did not realise that Good was in effect acting as a courier, carrying Princeton ideas to himself and Williams—or that Newman had played a similar role in his 1947 lectures. The logical design of the 1948 Baby is in fact virtually identical to a 1946 Princeton design by von Neumann and his group—a finding that places the Manchester Baby in a very new light.

Turing[71]

From the beginning Newman's plan had been that, in order to have a computer ready for experimental work as soon as possible, 'one of the types already under construction in 1946 should be copied'.[246] Huskey, who paid a visit early in 1947 to the Newman–Williams project (as he called it) said in his write-up of the visit: 'They are planning to more or less copy the von Neumann scheme'.[247] Despite Kilburn's flirtation with a Turingesque design later in 1947, the 1948 Baby was a very close relative indeed of the (more complex) machine described in von Neumann's 'Preliminary Discussion of the Logical Design of an Electronic Computing Instrument'.[248] Both were single-address machines with a central accumulator.[249] Moreover the **control arrangements** for the two machines were virtually identical.[250] Simplifications were achieved in the Baby by (i) using much less memory than von Neumann specified, (ii) using fewer basic operations, (iii) using a more restricted form of conditional transfer of control (**see above**), (iv) storing only one instruction per word, rather than two as in the Princeton design, and (v) opting for a serial design. The Princeton design involved 40 memory units working in parallel.[251] (Kilburn's view on parallelism? 'Given unlimited money, quite right!'[252])



The National Science Foundation 'family tree' of computer design (1957)[72] **Click to enlarge in new window**

Huskey's 1947 summary of logical aspects of the Princeton design (published in *Alan Turing's Automatic Computing Engine*) makes it obvious that the design of the Baby adhered very closely to American thinking. Aside from Kilburn's idea of using subtraction as the single basic arithmetical operation, the basic **logical structure** of the Baby was more or less identical to that being proposed at Princeton. Huskey wrote in 1947:

> **Princeton. In the von Neumann plan the machine consists essentially of a memory and a static accumulator. All transfers from the memory to the accumulator are essentially additions. The orders used are of the following type:**
>
> **(1) Clear A** This clears the accumulator.
>
> **(2) x to A** Adds the number in position x in the memory to the contents of the accumulator.
>
> **(3) A to x** Transfers the number in the accumulator to position x of the memory.
>
> **(4) C to x** Transfers control to x; i.e., the next order to be obeyed is in position x in the memory.
>
> **(5) CC to x** Conditional transfer of control; i.e., control is transferred to x in the memory if the number in

A is negative. Otherwise, control obeys consecutive orders in the memory.[253]

The Baby's originality certainly does not lie in its logical design, but in its cathode ray tube memory and its electronic engineering. It was as electronic engineers, not computer architects, that Williams and Kilburn led the world in 1948.

Just as key logical ideas flowed from Princeton to Manchester, key engineering ideas flowed in the opposite direction. A pre-publication version of the Williams–Kilburn report 'A Storage System for Use with Binary Digital Computing Machines'[254] was read eagerly at Princeton in June 1948.[255] As soon as von Neumann's chief engineer **Julian Bigelow** read about the Williams Tube he 'realized at once that it could be used exactly as we wished' (wrote von Neumann's collaborator Herman Goldstine).[256] Since 1946 von Neumann's plan had been to use the RCA Selectron memory tube, under development elsewhere in Princeton, but by 1948 this was still nowhere close to working. In the summer of 1948 Bigelow travelled to Manchester to see the Williams Tube memory in operation.[257] He was impressed by what he described as Williams' 'inventive genius'.[258]

When the Princeton computer was eventually completed in 1951, its main memory consisted of **40 Williams Tubes**.[259] The Williams Tube, said Goldstine, made 'a whole generation of electronic computers possible'.[260] Another Manchester invention to travel to Princeton (although not in time to be incorporated in the Princeton computer)[261] was the index register, or 'B-tube',[262] for which Kilburn, Newman, Tootill and Williams shared the patent.[263] Goldstine described the index register as a 'very significant modification instituted by Kilburn of the Manchester group' (although Kilburn's name did not come first on the patent).[264] Index registers, which enable instructions to be modified while the program is running, are now a standard part of computer technology.

von Neumann[73]

13. Turing Joins the Manchester Project

In May 1948 Turing resigned from the NPL. Work on the ACE had drawn almost to a standstill (see chapter 20 **Third Attempt to Build the ACE: the Disastrous Thomas Era** and chapter 21 **Turing Leaves the NPL**). Newman lured a 'very fed up'[265] Turing to Manchester, where he was appointed Deputy Director of the Computing Machine Laboratory (there was no Director).

Once Turing arrived in Manchester he got the computer working properly, designing an input mechanism and the programming system[266] for an expanded machine, and he wrote a **programming manual**.[267] The first of the production models, marketed by Ferranti, was completed in February 1951 and was the first commercially available electronic digital computer.[268] The first U.S. commercial machine, the Eckert–Mauchly UNIVAC, was delivered a few weeks later in March 1951.[269]

Jack Good, codebreaker and computer pioneer[74]

In a letter Williams described what was, from his point of view as an engineer, Turing's 'major contribution' to the full-scale machine:

> Our first machine had no input mechanism except for a technique for inserting single digits into the store at chosen places. It had no output mechanism, the answer was read directly from the cathode ray tube monitoring the store. At this point Turing made his, from my point of view, major

> **contribution. He specified simple minimum input facilities from five hole paper tape and output from the machine in similar form.**[270]

This five-hole paper tape was the daily bread of Bletchley's attack on **Tunny**. So too was the five-bit teleprinter code which Turing used at Manchester to express machine-code programs in the form of keyboard characters.

Elsewhere Williams provided some additional detail. Turing explained to the engineers

> **how you could organise a paper tape input machine to load a computer. ... [Turing] was of immense value to us in telling us precisely what signals he would need to operate his tape input machine, precisely what signals he would need to operate his tape punch.**[271]

This input machine employed a row of photocells to read the moving teleprinter tape—technology similar to that used in Colossus and Heath Robinson. The device delivered input to the Manchester computer at the rate of 200 five-bit characters per second, which approached the maximum that the computer was able to handle.[272] This represented only 4% of the normal input rate of Colossus I, however![273]

Turing and Newman also contributed to the instruction set of the full-scale computer.[274] Tootill said:

> **As well as our own ideas, we incorporated functions suggested by Turing and Newman in the improvement and extension of the first machine. When I did the logic design of the Ferranti Mark 1, I got them to approve the list of functions.**[275]

Kilburn reported that at this time (1949) Newman contributed another key idea to the plans for the full-scale computer: the concept of multilength numbers.[276] Newman proposed that a facility be included in the machine for linking together arbitrary numbers of words of memory, so that arithmetical operations could be carried out on numbers of various lengths. This idea was present in Version V of Turing's ACE design (1946).[277]

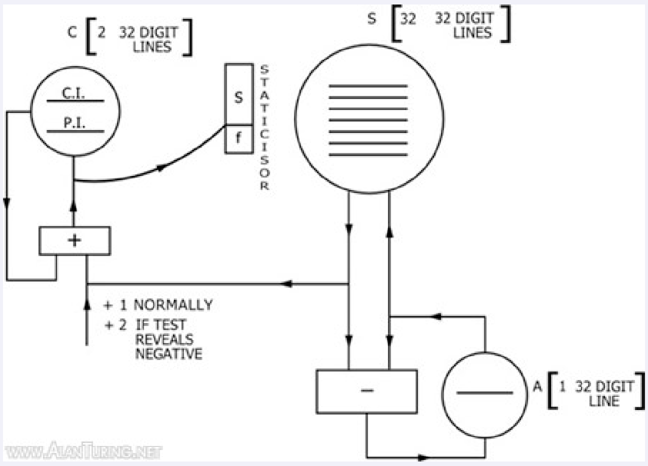
At Manchester Turing at last had his hands on a stored-program computer. He was soon using Manchester University's Ferranti Mark I to model biological growth (see chapter 10 **Turing and Artificial Life**). And while the rest of the world was just waking up to the idea that electronics was the new way to do binary arithmetic, Turing was talking very seriously about programming digital computers to think (see chapter 9 **Turing and Artificial Intelligence**).

14. Other Early Stored Program Computers

The EDSAC, built by Maurice Wilkes at the University of Cambridge Mathematical Laboratory, was the second electronic stored-program computer to run, in May 1949. (It was at a conference held in June 1949 to celebrate the inauguration of the EDSAC that Turing presented his early paper on what is now called program verification, 'Checking a Large Routine'.[278])

Later in 1949 came: the BINAC, built by the creators of the ENIAC, Eckert and Mauchly, at their Electronic Control Company, Philadelphia

The fog disperses at the Princeton Institute for Advanced Study. Photo © Thomas Uphill.



The Baby[68]

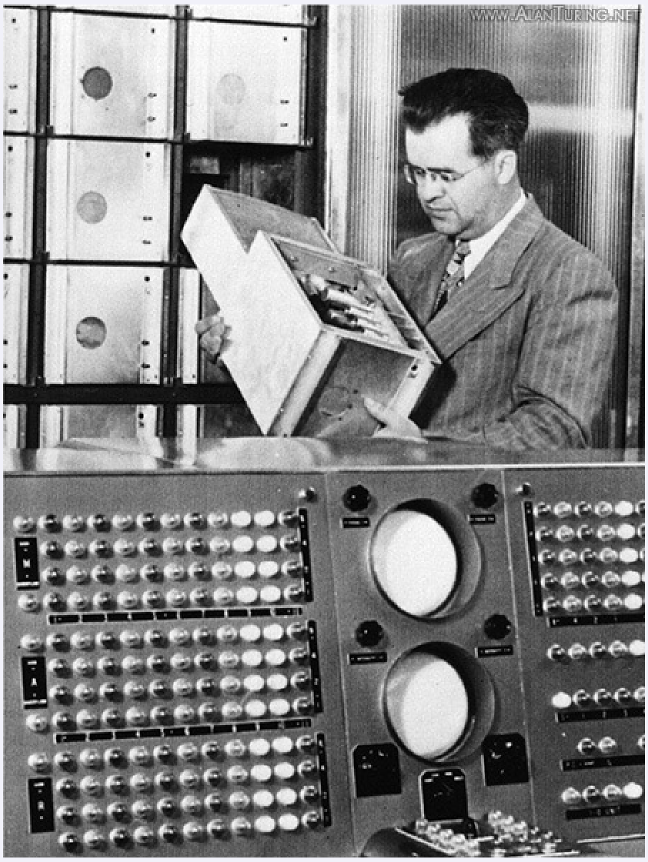
Members of the Princeton computer team. From left: John von Neumann, Julian Bigelow, James Pomerene, Herman Goldstine.[75]

(opinions differ as to whether the BINAC ever actually worked); the CSIR Mark 1, built by Trevor Pearcey at the Commonwealth Scientific and Industrial Research Organisation Division of Radiophysics, Sydney, Australia; and Whirlwind I, built by Jay Forrester at the Digital Computer Laboratory, Massachusetts Institute of Technology.

The SEAC, built by Samuel Alexander and Ralph Slutz at the U.S. Bureau of Standards in Washington D.C., first ran in April 1950; and the SWAC, built by Harry Huskey at the Institute for Numerical Analysis on the campus of the University of California at Los Angeles, in August 1950.

While the EDVAC itself was not fully working until 1952, most of the computers just mentioned were influenced by the EDVAC design.

The Princeton IAS computer. 20 Williams Tubes in cannisters are visible; another 20 are on the opposite side of the machine.[76]



Harry Huskey examining one of the SWAC's 40 Williams Tubes[77]

Kilburn standing at the console of the Ferranti Mark I computer at Manchester University. Seated are Ferranti engineers Keith Lonsdale (left) and Brian Pollard.[78]

Turing standing at the console of the Ferranti Mark I computer at Manchester University. Here Turing pioneered the field of research now called Artificial Life.[79]

The EDSAC, built by Maurice Wilkes at the University of Cambridge[80]

Harry Huskey at the console of the SWAC (National Bureau of Standards Western Automatic Computer)[81]

Turing[82]

Alan Turing, Father of the Modern Computer

Part II

The ACE of Disappointments: Turing's Struggle to Build His Electronic Brain

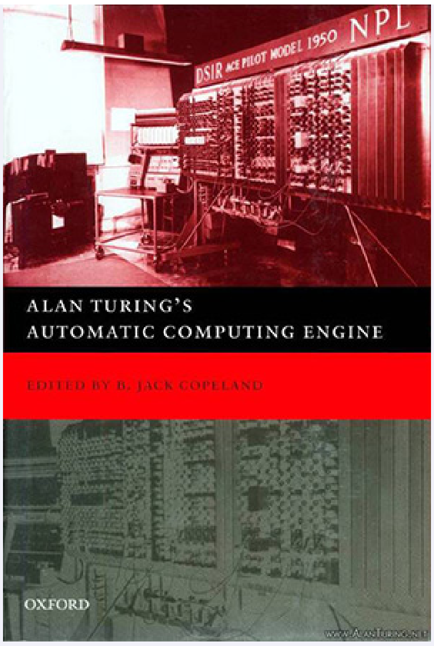
Contents

15. Womersley Recruits Turing to the National Physical Laboratory

The name 'Automatic Computing Engine' was due to Womersley, the administrative head of the ACE project,[288] and the story of the ACE begins with his appointment as Superintendent of the newly created Mathematics Division of the National Physical Laboratory.[289] Womersley's proposed research programme for his new Division included the items 'To explore the application of switching methods (mechanical, electrical and electronic) to computations of all kinds', 'Investigation of the possible adaptation of automatic telephone equipment to scientific computing', and 'Development of electronic counting device suitable for rapid computing'.[290]

Womersley had himself been a member of the Interdepartmental

Technical Committee that in April 1944 had recommended the creation at the NPL of a Mathematics Division whose primary objective was to 'undertake research into new computing methods and machines'.[291] In its report the Committee emphasized that the new division should be provided with 'facilities for designing new machines and perhaps for constructing pioneer ones', noting 'it is probable that new machines may be called for of patterns that cannot be foreseen now'.[292]



For a complete history of the ACE, see **Alan Turing's Automatic Computing Engine** (Oxford University Press, 2005, ed. Copeland). Contains material by Turing and his contemporaries.

In December 1944 Womersley addressed the Executive Committee of the NPL on the potential of electronic computing. His proposals were far-sighted at a time when no electronic computers were in existence apart from the—invisible—Colossus. The minutes of the meeting summarize his speech:

> **Electronic counting devices ... can be used and machines can be constructed which have a high degree of flexibility and which can be continually improved and extended. Electronic counting can be done at the rate of one operation per microsecond, a vast improvement on anything previously attempted. All the processes of arithmetic can be performed and by suitable inter-connections operated by uniselectors a machine can be made to perform certain cycles of operations mechanically... . [T]here is no reason why the instructions to the machine should not depend on the result of previous operations so that various iterative types of method could become fully automatic.**[293]

In November 1946 Womersley wrote a fascinating synopsis of the principal events that led to the establishment of the ACE project:

> **1936-37 Publication of paper by A. M. Turing 'On Computable Numbers, with an Application to the Entscheidungsproblem'... .**
>
> **1937-38 Paper seen by J.R.W. [J.R. Womersley] and read. J.R.W. met C.L. Norfolk, a telephone engineer who had specialised in totalisator design and discussed with him the planning of a 'Turing machine' using automatic telephone equipment. Rough schematics prepared, and possibility of submitting a proposal to N.P.L. discussed. It was decided that machine would be too slow to be effective.**
>
> **June 1938 J.R.W. purchased a uniselector and some relays on Petty Cash at R.D. Woolwich for spare-time experiments. Experiments abandoned owing to pressure of work on ballistics... .**
>
> **1942 Aiken's machine [the Sequence-Controlled Calculator at Harvard University] completed and working.**
>
> **1943 Stibitz constructed the Relay Computor at Bell Telephone Laboratories.**[294]
>
> **Late 1943 J.R.W. first heard of these American machines.**


Howard Aiken and the Automatic Sequence-Controlled Calculator[83]

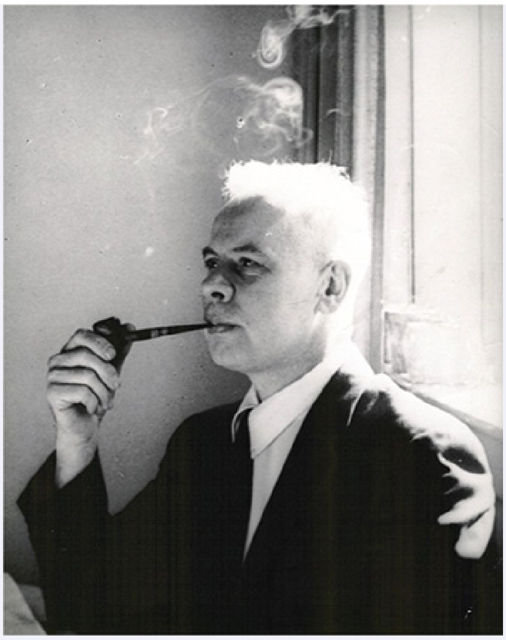
1944 Interdepartmental Committee on a Central Mathematical Station. D.R. Hartree mentioned at one meeting the possible use of automatic telephone equipment in the design of large calculating machines. J.R.W. submitted suggestions for a research programme to be included in Committee's Report.

1944 Sept. J.R.W. chosen for Maths. Division.

1944 Oct. J.R.W. prepares research programme for Maths. Division which includes an item covering the A.C.E.

1944 Nov. J.R.W. addresses Executive Committee of N.P.L. Quotation from M/S (delivered verbatim) ...

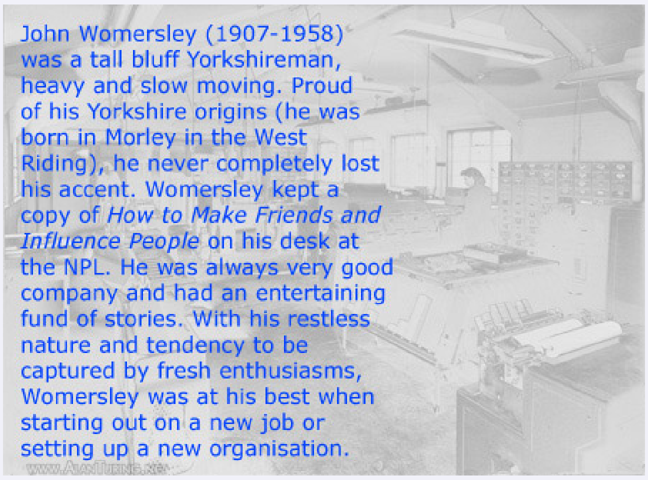
'Are we to have a mixed team developing gadgets of many kinds ... Or are we, following Comrie ... to rely on sheer virtuosity in the handling of the ordinary types of calculating machines? I think either attitude would be disastrous ... We can gain the advantages of both methods by adopting electronic counting and by making the instructions to the machine automatic ... '



George Stibitz at Bell Labs[84]

1945 Feb-May J.R.W. sent to the U.S.A. by Director. Sees Harvard machine and calls it 'Turing in hardware'. (Can be confirmed by reference to letters to wife during visit). J.R.W. sees ENIAC and is given information about EDVAC by Von Neumann and Goldstine.

1945 June J.R.W. meets Professor M.H.A. Newman. Tells Newman he wishes to meet Turing. Meets Turing same day and invites him home. J.R.W. shows Turing the first report on the EDVAC and persuades him to join N.P.L. staff, arranges interview and convinces Director and Secretary.[295]



It has not been possible to locate a photograph of Womersley. The background shows the inside of the Babbage Building, part of Womersley's Mathematics Division.

Persuading Turing to join the embryonic ACE project was a great coup, testifying to Womersley's vision and initiative (even locating Turing, who was at that time engaged in secret work, could not have been straightforward). Turing was even more highly qualified for the job than Womersley realised. While Womersley clearly understood the importance of Turing's pre-war article 'On Computable Numbers, with an Application to the Entscheidungsproblem', he was completely unaware of the highly secret developments in electronic computing that had taken place during the war at Bletchley Park, where Turing was among the few who knew of **Colossus**.

16. Turing's Design Document 'Proposed Electronic Calculator'

Turing's employment at the NPL commenced on 1 October 1945, by which time Mathematics Division was 'functioning on a limited scale'.[296] Turing set to work on the design of the Automatic Computing Engine. By the end of 1945 he had completed his technical report 'Proposed Electronic Calculator'.[297] Womersley's next step was to present Turing's design to the Director of the NPL,

Darwin, in order to secure the support necessary for the project. He wrote to Darwin:

"ACE" Machine Project.

With this minute I present three reports. The first is a short account, by Hartree and myself, of recent developments in the U.S.A. in the field of automatically controlled calculating machines. The second is a report by Dr. A. M. Turing which shows how such a machine could be constructed (by combining electrical apparatus already well-developed and having known properties) which would be capable of solving a wide variety of problems at speeds hitherto unattainable.

It is very important to mention that this device is not a calculating machine in the ordinary sense of the word. One does not need to limit its functions to arithmetic. It is just as much at home in algebra, i.e. it can work out matrix multiplications in which the elements are algebraic polynomials, or problems in Boolean Algebra, or the enumeration of group characters. Methods of successive approximation, i.e. the Southwell "Relaxation" process, are equally possible, since the machine will contain a device which enables it to choose between two sets of instructions according to the sign of some number in it.

The cost is, naturally, a doubtful point. I put it, after careful consideration, at £60,000 - £70,000, though it is difficult to be sure of a "ceiling". It will, I believe, be one of the best bargains the D.S.I.R. [Department of Scientific and Industrial Research] has ever made. To give some idea of the speed of the machine, it will calculate a gun trajectory, from muzzle to point of fall, in less than 30 seconds, and it would carry through the preparation of the whole of the ballistic bombing tables for the R.A.F. in a few weeks, apart from printing. By its use we can explore whole fields of both pure and applied mathematics at present closed to us by the formidable magnitude of the computing programmes involved.

We can attack complicated integral equations, integro-differential equations and partial differential equations by replacing them by large blocks of simultaneous linear equations in 700-1000 unknowns and solve them with ease and speed. We can take T. Smith's theory of the design of optical instruments and use it on practical design problems at a speed which will enable answers to be given to the firms by telephone in a few hours. We can revolutionise the study of compressible fluid flow, and of aircraft stability.

BRITAIN TO MAKE A RADIO BRAIN

"Ace" Superior To U.S. Model

BIGGER MEMORY STORE

Britain is to make a radio "brain" which will be called "Ace," at a cost of between £100,000 and £125,000, it was announced by the Department of Scientific and Industrial Research last night. Only one will probably be made.

Ace stands for automatic computing engine. The machine will work at least as fast as the American invention called Eniac (electronic numerical integrator and computor).

The invention of Eniac was disclosed by Viscount Mountbatten when he spoke at the dinner of the British Institution of Radio Engineers last Thursday. The machine, which cost £100,000, used 18,000 valves and 5,000 switches and consumed as much power as 100 electric radiators.

The memory storage of Ace will be higher than the American invention—75,000 decimal digits compared with 200, and by means of an exhaustive library of prefabricated instructions contained on specially punched cards, the English machine will be able to deal with more complex instructions.

TIME SAVED

The organisation of these prefabricated instructions will obviate the laborious system of plugs and switches employed in Eniac, that British scientists of the mathematics division of the National Physical Laboratory feel that they have made an important new contribution.

Instructions may take a couple of minutes compared to two hours on Eniac.

Numbers are represented by a series of 1's and 0's, and answers will be given in the decimal system. The machine will multiply two 10-figure numbers in 2,000ths of a second.

Well within its scope will be the class of problem which, by its extreme complexity and the enormous length of time needed to solve it, is almost an impossibility for the pencil and paper worker. It will, for instance, be able to tackle simultaneous equations with 50 or 100 unknowns.

THREE YEARS TO BUILD

It will be able to cope by itself with all the abstruse problems for which it is designed. Further

Problems now slowly attacked piecemeal will be capable of solution as a whole. The machine will also grapple successfully with problems of heat-flow in non-uniform substances, or substances in which heat is being continuously generated. It will enable the study of materials with peculiar elastic properties (e.g. plastics) to be advanced in a way that is impossible with present computing resources... . [W]e could alter the whole tempo of the numerical mathematical work associated with the scientific research of this country if the machine were available.

The possibilities inherent in this equipment are so tremendous that it is difficult to state a practical case to those who are not au fait with the American developments without it sounding completely fantastic. But if anyone is going to suggest that this equipment is expensive, may I point out that two machines in the U.S.A., the Harvard Sequence Controlled Calculator, and the Bell Telephone Laboratory Relay Computer, cost as much an this, work at 1/1000th the speed, will have neither the versatility nor the storage capacity, and yet were thought by the Americans to be worth while.

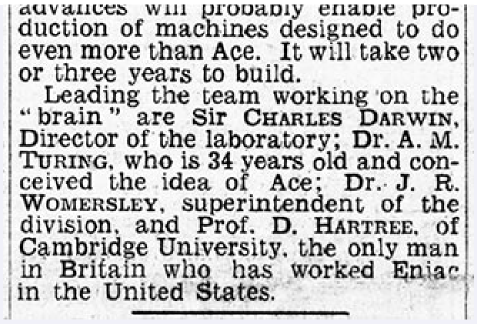
The third document is an attempt to state a practical case for the equipment. In view of the unique nature of the equipment this is difficult, but I believe that in this direction the promised support of Commander Sir Edward Travis, of the Foreign Office, will be invaluable.[298]...

As regards the manufacture of the machine, I think that the Post Office Engineering Research Station is the right place, if they can see their way to do it. Mr. Flowers, of that Station, has had wartime experience in the right field, and, during his recent visit to the U.S.A., visited the places where these developments have been going on.[299]

Approval for the ACE project rested with the Executive Committee of the NPL and Womersley duly prepared a paper for presentation to the Committee:

Memorandum by Mr. J. R. Womersley, Superintendent, Mathematics Division

The research programme of the Mathematics Division contains an item "To explore the application of switching methods (mechanical, electrical and electronic) to computations of all kinds." ... Dr. A. M. Turing was appointed to the staff of the Division, and began to consider the possibilities of electronic methods ... Dr. Turing has now completed a long report, which makes definite proposals for the


advances will probably enable production of machines designed to do even more than Ace. It will take two or three years to build.
Leading the team working on the "brain" are Sir CHARLES DARWIN, Director of the laboratory; Dr. A. M. TURING, who is 34 years old and conceived the idea of Ace; Dr. J. R. WOMERSLEY, superintendent of the division, and Prof. D. HARTREE, of Cambridge University, the only man in Britain who has worked Eniac in the United States.

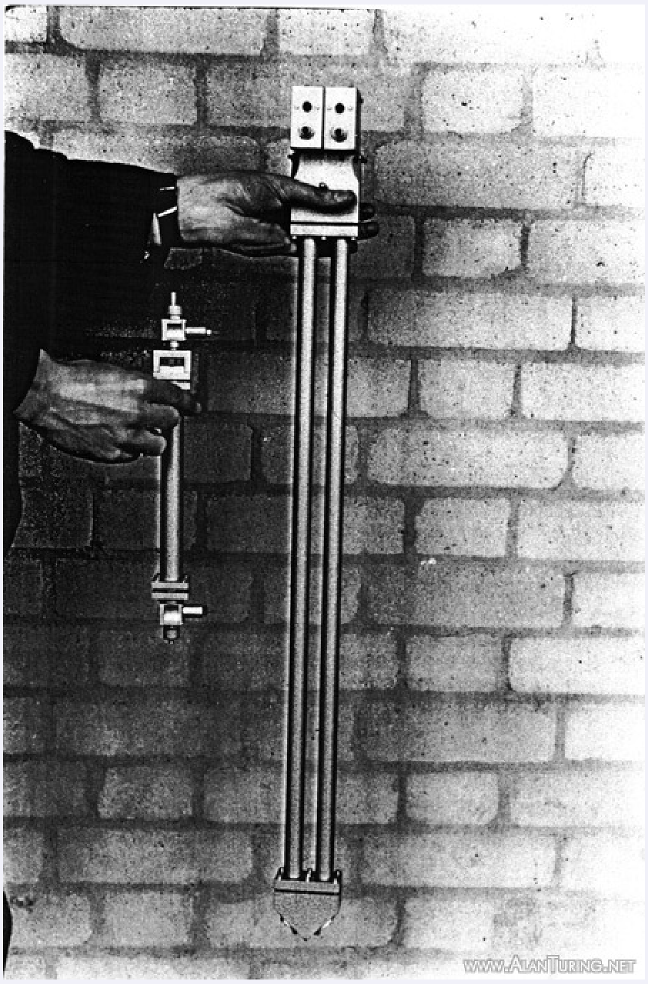
The Daily Telegraph, 7 November 1946[85] construction of a machine, capable of solving a wide variety of problems at speeds hitherto unattainable... .

Summary of Part I of Dr. Turing's Report

It is intended that the ACE machine shall tackle whole problems, i.e. that instead of repeatedly using human labour for taking material out of the machine and putting it back at the appropriate moment, all this will be done by the machine itself. It will not be limited to carrying out a sequence of prescribed operations. Provision is made for making the behaviour of the machine to depend on the results of its own calculations.

Once the human element is eliminated, the increase in speed is enormous. For example, it is intended that the multiplication of two ten-figure numbers shall be carried out in 500 microseconds, about 20,000 times the speed of a normal calculating machine. This speed is not attained by making the equipment more expensive and more elaborate than it need be. It is the natural result of the unconventional methods used, and once this is granted, there is no economy to be obtained by reducing it.

The basic principle is that numbers contained in the machine are stored dynamically, not statically as in other machines. The internal working of the machine is entirely in the binary system, and a number is represented by a series of 1's and 0's, the 1's being pulses, and the 0's the spaces between them. The digit of least significance comes first in point of time. The problem is to find a way of storing a number in this form, so that it can be kept circulating in the machine until it is needed again for use in a subsequent calculation. Dr. Turing describes a 'delay line,' the 'circulating memory' used in radar, which he shows to be suitable for this purpose. The manufacture of memories capable of accommodating 1000 binary digits is shown to be practicable.



Mercury delay lines[86]

The machine then divides into two main parts, an arithmetical organ, and a logical control, with input and output organs for communication with the outside world. The instructions to the machine can themselves be expressed in the form of numbers in the binary scale, and fed into the logical control part of the machine at the beginning of a problem. There they circulate in the appropriate delay lines until the numerical information ("initial conditions") has been fed in, the final information being another instruction, the "instruction to proceed."

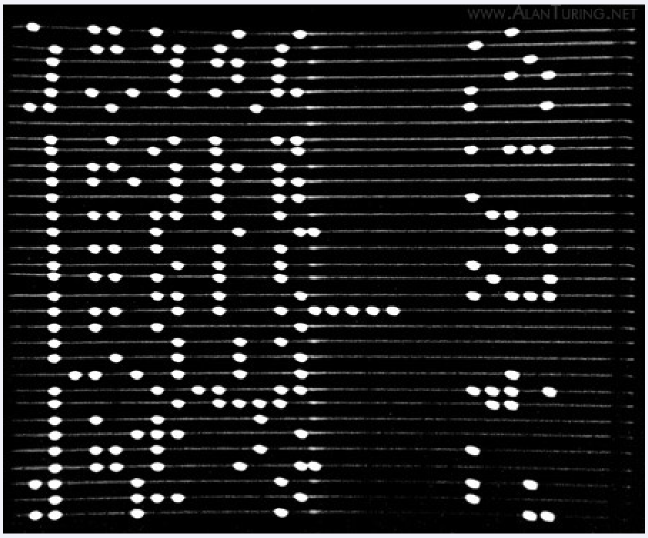
... The original intention was that each unit would consist of 32 binary digits, the first digit being '0' or '1' according to the nature of the 'number' i.e. whether it is a number or an instruction, the second being an indication of sign. Dr. Turing has extended this idea to make it more flexible. Each 'number' consists of two units of 32 binary digits. One of these contains a number in the binary system between zero and unity, the other gives its 'significance,' i.e. a power of 2 by which it must be multiplied, its sign, and some spare digits which are used to identify the number.

The processes of arithmetic are very simple. To add two numbers they are taken out of storage and by passing them through a simple network of radio valves, they are 'glued' together and the sum deposited in another storage element.

Multiplication is done by repetitions of this process, with appropriate time delays. It is proposed to do division by multiplication by the reciprocal, the reciprocal being calculated by successive approximation. This is quite practicable in view of the high speed of the unit processes.

The scope of the machine is very wide. It is envisaged that the construction of a set of range tables could be treated as a single problem, and that once experience is gained, could be run off in a few days. As an indication of speed, it should be possible to calculate a gun trajectory by 'small arcs' from muzzle to point of fall, in about half a minute. All types of 'relaxation' calculation can be fully mechanised - indeed all methods of successive approximation. Matrices of degree less than 30 whose elements are polynomials of the tenth degree can be multiplied, giving another matrix with polynomial coefficients. Other examples are given in the report. Some attention is also given to the problem of checking, since the machine must inspire confidence in its results. This cannot be dealt with adequately until actual manufacture begins... .

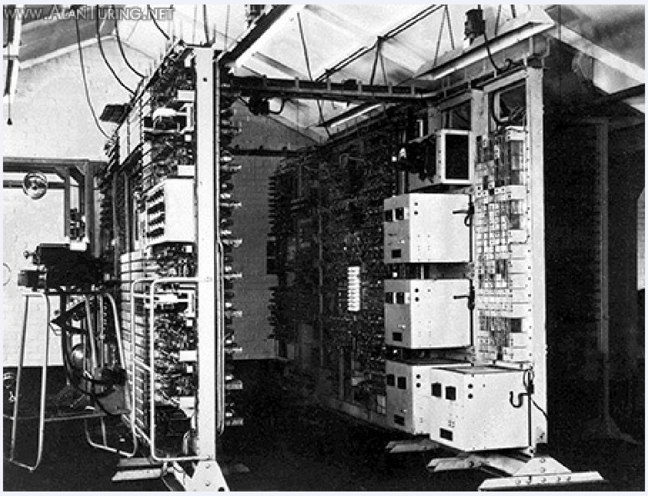
The cost of the proposed machine will be about the same as the ENIAC constructed for the Aberdeen Proving Ground, and somewhat less than the Bell Telephone Relay Computer. The cost of the Harvard University machine is not known with accuracy, but is reputed to be half-a-million dollars. If it is granted that this country should possess one of these large machines, the Mathematics Division of the N.P.L. is the obvious place for it. The machine envisaged by Dr. Turing would have an output equal to the total output of all the large machines so far



Instructions in a delay line, viewed on a monitor[87]

constructed in the U.S.A. In fact we are now in a position to reap handsome benefits from the pioneer work done in the United States, and it is undoubtedly advisable that we should build this type of machine at once, rather than begin with relay equipment.[300]

As mentioned previously, Womersley had no knowledge of Colossus. Consequently his view of the technological developments in computing was distorted, and he tended to exaggerate the intellectual debt owed by the ACE to the ENIAC and to the relay (i.e. non-electronic) machines at Harvard and Bell Labs.



Colossus VII[88]

Womersley's Memorandum and Turing's 'Proposed Electronic Calculator' were submitted to the Executive Committee of the NPL in February 1946. Discussion was deferred until the March meeting, when the 'Committee resolved unanimously to support with enthusiasm the proposal that Mathematics Division should undertake the development and construction of an automatic computing engine of the type proposed by Dr. A. M. Turing'.[301] The minutes of the meeting recorded Womersley's opening remarks, Turing's short lecture, and the ensuing discussion:

Large Electronic Calculating Machine ACE

The Committee had before it Paper E.881 (Memorandum by Mr. J. R. Womersley, Superintendent, Mathematics Division, concerning the "ACE" Machine Project) and Paper E.882 (Report by Dr. A. M. Turing On Proposals for the Development of an Automatic Computing Engine (ACE)).

The Chairman invited Mr. Womersley to outline the reasons why a machine of the type proposed by Dr. Turing should be constructed for the Mathematics Division.

Mr. Womersley said that he believed it possible to see these proposals in their true perspective if one had knowledge of what had been done in the U.S.A. during the war. He therefore proposed to begin by sketching in some of the background of recent developments.

Mr. Womersley then gave a brief description of three large calculating devices constructed in the U.S.A. during the war - the I.B.M. Sequence Controlled Calculator at Harvard University, the Relay Computer designed by Dr. G. R. Stibitz of Bell's Telephone Laboratories, and the ENIAC, constructed at the Moore School of Electrical Engineering, University of Pennsylvania for the Ballistics Research Laboratories, Aberdeen Proving Ground. Each one of these machines had cost from £80,000-£100,000. It was interesting to note that Dr. Turing's machine, when fully completed, would have a potential output of work greater than the three of them put together. In other words, we now had the opportunity to begin work in this field at a most favourable moment. The machine proposed had not only a greater output, but greater

versatility than the machines so far made, because of the greater elaboration of the logical controls proposed by Dr. Turing. This was possible by reason of the different mode of operation, and the fact that in Dr. Turing we had available an expert in the field of mathematical logic.

Mr. Womersley then introduced Dr. A. M. Turing, who was invited to describe the principles underlying his proposal.

Dr. Turing explained that if a high overall computing speed was to be obtained it was necessary to do all operations automatically. It was not sufficient to do the arithmetical operations at electronic speeds: provision must also be made for the transfer of data (numbers, etc.) from place to place. This led to two further requirements - 'storage' or 'memory' for the numbers not immediately in use, and means for instructing the machine to do the right operations in the right order. There were then four problems, two of which were engineering problems and two mathematical or combinatory.

Turing[14]

Problem (1) (Engineering). To provide a suitable storage system.

Problem (2) (Engineering). To provide high speed electronic switching units.

Problem (3) (Mathematical). To design circuits for the ACE, building these circuits up from the storage and switching units described under Problems 1 and 2.

Problem (4) (Mathematical). To break down the computing jobs which are to be done on the ACE into the elementary processes which the ACE is designed to carry out (as determined in the solution of Problem 3). To devise tables of instructions which translate the jobs into a form which is understood by the machine.

Taking these four problems in order, Dr. Turing said that a storage system must be both economical and accessible. Teleprinter tape provided an example of a highly economical but inaccessible system. It was possible to store about ten million binary digits at a cost of £1, but one might spend minutes in unrolling tape to find a single figure. Trigger circuits ['flip-flops'] incorporating radio valves on the other hand provided an example of a highly accessible but highly uneconomical form of storage; the value of any desired figure could be obtained within a microsecond or less, but only one or two digits could be stored for £1. A compromise was required; one suitable system was the 'acoustic delay line' which provided storage for 1000 binary digits at a cost of a few pounds, and any required information could be made available within a millisecond. Dr. Turing explained the principle of the delay line, which involved transmitting compression waves down a tube of liquid, using piezo crystals both as transmitters and receivers of sound. The output of the receiving crystal was amplified, restored to its ideal shape and fed back to the transmitter. On account of the shape restoring process it was possible for a signal to travel down the tube many millions of times and remain recognisable.

Dr. Turing then gave a brief account of the high speed switching problems involved in the ACE (Problems (2) and (3)). Numbers were to be represented in the binary scale and valves were only to be used as 'on-off' devices. Although switching units had not yet been made there was every hope of success because the limiting factors were electron transit time, and the allied quantity O_{ag}/g_m, and the frequencies at which these became serious were well above those at which the ACE would be operated (viz. about 1 Mc/s). Switching circuit design (Problem (3)) was illustrated by means of the adder circuit.

Time did not permit of an adequate account of Problem (4).

In reply to a question from Professor Tyndall, Dr. Turing explained that an elaborate system of checks would be incorporated, so that the failure of any part would be immediately indicated. It was not possible entirely to guard against the failure of the checking system itself, but the probability of an undetected error could be reduced to very small proportions. The majority of the checks would be introduced through instruction tables and would therefore require no special equipment.

The Director asked what would happen if the machine were instructed to sum a series which actually diverged although thought to converge. Dr. Turing replied that it was left to the discretion of the man who constructed the instruction tables (the controller) to state what the machine should do in these cases. The summation could be specified to a given number of terms regardless of convergence, or until the last term was less than a given amount; preferably the controller should have worked out the theory of the convergence to some extent so as to be able to incorporate a suitable test. The Director asked what would happen in cases where the machine was instructed to solve an equation with several roots. Dr. Turing replied that the controller would have to take all these possibilities into account, so that the construction of instruction tables might be a somewhat "finicky" business.

Professor Hartree pointed out that the serial operation of the machine makes it very economical in its use of radio valves. It requires only 2000 valves as against 18000 in the ENIAC, and gives a "memory" capacity of 6000 numbers compared with the 20 numbers of the ENIAC. This greater capacity (and the higher speed) are attained at no greater cost than the ENIAC. The greater storage capacity is facilitated by the high speed, and this is an important factor in gaining the economy in equipment.

Professor Hartree also pointed out that if the ACE is not developed in this country the U.S.A. will sweep the field, and reminded the Committee that this country has shown much greater flexibility than the Americans in the use of mathematical hardware. He urged that the machine should have every priority over the existing proposal for the construction of a large differential analyser.

Director enquired whether the machine could be used for other purposes if it did not fulfil completely Dr. Turing's hopes. Dr. Turing replied that this would depend largely on what part of the machine failed to operate, but that in general he felt that many purposes could be served by it.

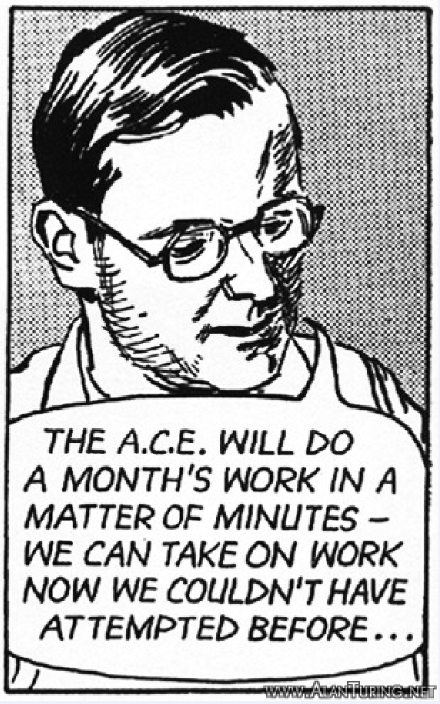
There was next some discussion as to the possible cost of the machine and Mr. Womersley said that a pilot set-up could possibly be built for approximately £10,000, and it was generally agreed that no close estimate of the overall cost of the full machine could be made at this stage. As regards financing the project, the Secretary stated that the initiation of the work could be undertaken within the terms of the existing research programme of Mathematics Division and that it was probable that sufficient financial provision had been made for possible expenditure during the 1946-7 financial year. It appeared desirable, however, that the possible magnitude of the project should be understood by Headquarters and the Treasury so that, as far as possible, assurance could be obtained that work on the machine could be continued in succeeding years in so far as financial provisions are concerned.

Professor Hartree said that such a machine would be a means for tackling completely new ranges of problems, and Dr. Southwell reported that Professor G. I. Taylor had expressed the opinion that the machine would be more useful than ENIAC. He hoped, however, that when the machine was constructed, charges made for its use would not be so high as to discourage its use by Universities, etc. He felt that there should be no attempt at amortisation of the cost of the machine, which might well run into £100,000, but that this should be regarded as a contribution of the Laboratory to the general good of the country.

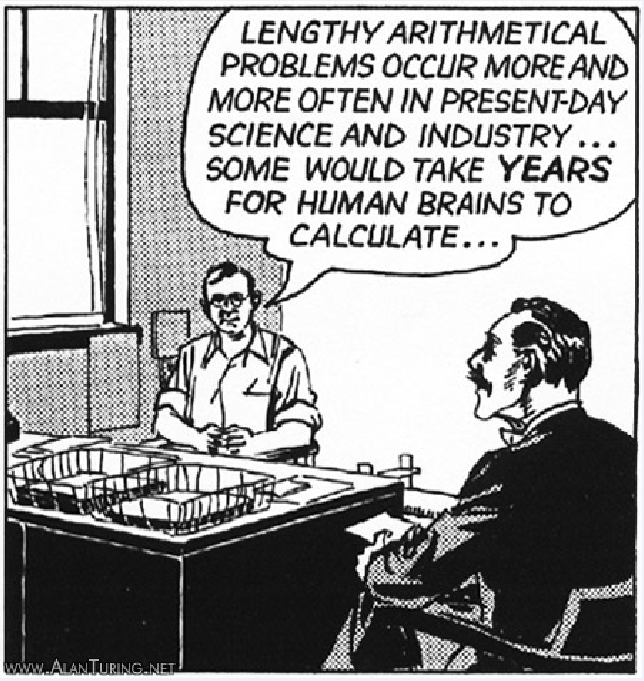
The Committee resolved unanimously to support with enthusiasm the proposal that Mathematics Division should undertake the development and construction of an automatic computing engine of the type proposed by Dr. A. M. Turing and Director agreed to discuss the financial and other aspects of the matter with Headquarters.

In a letter, Dr. E. T. Paris expressed the interest of Ministry of Supply in the development of such a machine, and stated that he had consulted Colonel Phillips, Superintendent of Applied Ballistics, and Dr. McColl, Superintendent of Theoretical Research in Armaments, who foresaw that from their point of view the main use of the machine would be for - (a) The calculations of trajectories for all types of projectiles (shell, bombs, rockets and guided missiles); (b) Internal ballistic calculations (the motion of projectiles down the bore); (c) The solution of partial differential equations by relaxation and characteristic methods. Dr. Paris also enquired how soon the machine was likely to be a working concern and to what extent it was likely to be available for use by his Ministry, adding that if the project goes well, at a later date it would be possible to consider whether it would be advisable to have a machine of the same general type made for armaments research and allied work.

In reply to a question by Dr. Carroll, Mr. Womersley said that as a very rough estimate he thought the cost of duplicating the machine would be approximately 25 per cent of the original cost, although the capacity of the machine would be such that duplicates would not be needed. He pointed out, however, that when such a machine is in use in his Division it will require the employment of a higher proportion of senior officers in the scientific class, because the machine itself will do much of the work of the lower staff classes.[302]



Newspaper cartoon of Wilkinson (Turing's assistant at the NPL from 1946) in 1952[89]

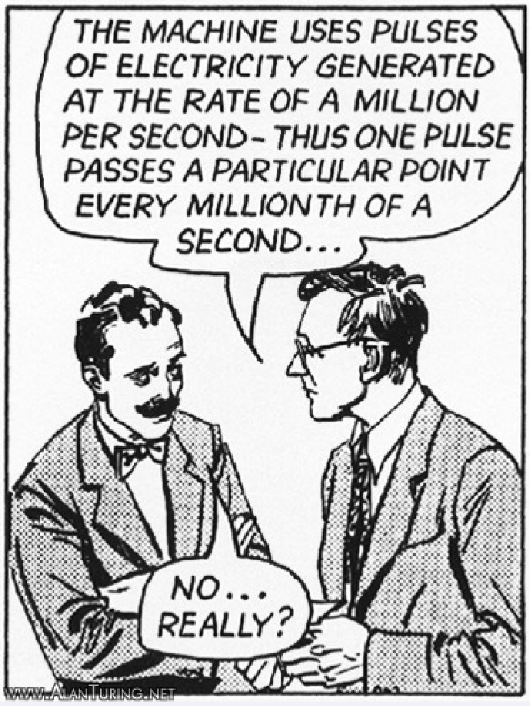


Cartoon of Wilkinson[90]

In April 1946 Darwin wrote as promised to 'Headquarters', the Department of Scientific and Industrial Research (DSIR). Notice his claim, mentioned earlier, that a single electronic computer might suffice for 'the whole country':

<u>Automatic Computing Engine (ACE)</u>

This is a proposal to construct a computing machine of very much greater potentialities than anything done hitherto, though a similar project is being worked out at present in America. The proposal has already been foreshadowed in the research programme of Mathematics Division, Item 6502 "To explore the application of switching methods (mechanical, electrical and electronic) to computations of all kinds." In the past the processes of computation ran in three stages, the mathematician, the computer [i.e. the human computer], the machine. The mathematician set the problem and laid down detailed instructions which might be so exact that the computer could do his work completely without any understanding of the real nature of the problem; the computer would then use the arithmetical machine to perform his operations of addition, multiplication, etc. In recent times, especially with use of punched card machines, it has been possible gradually for the machine to encroach on the computer's field, but all these processes have been essentially controlled by the rate at which a man can work.



Cartoon of Wilkinson[91]

The possibility of the new machine started from a paper by Dr. A. M. Turing some years ago, when he showed what a wide range of mathematical problems could be solved, in idea at any rate, by laying down the rules and leaving a machine to do the rest. Dr. Turing is now on the staff of N.P.L., and is responsible for the theoretical side of the present project, and also for the design of many of the more practical details. The principles he enunciated have now become practicable since it is possible to use electronics in the machine so that its rate of operation is about a hundred thousand times as fast as a man's. The proposed machine is primarily a system of electronic circuits some of which do the arithmetic, while others give the instructions in a codified form, also as numbers. But there is another feature necessary in computation, which may be called the memory; this corresponds to the fact that the human computer has at intervals to turn back to the results of some previous calculation and bring them forward again. In many ways the memory is the most serious problem in the machine, but a variety of methods have been proposed and some instruments have been made, and the choice among them is largely a matter of economy, since there will need to be several hundred organs of this type. At present it appears that the best solution may be one developed for use in radar, which consists in sending a stream of ultra-sonic pulses down a tube of liquid. These are known as delay lines and it is proposed that attention shall primarily be concentrated on

Cartoon of Wilkinson and the Pilot Model ACE in 1952[92] their use for this purpose. As at present planned the electronics will work at a rate of microseconds, and the memory tubes will store the information for a millisecond, or for any desired multiple of a millisecond.

Dr. Turing's proposals are set out in a paper (E.882) considered at the March, 1946 meeting of the Executive Committee of N.P.L. The Committee after discussing the problem with Mr. Womersley, Superintendent of Mathematics Division, and Dr. Turing, resolved unanimously to give the project its enthusiastic support.

An example of the sort of problem that could be solved is the calculation of ballistic trajectories. It is estimated that a full trajectory from muzzle to strike, worked out by small arcs, should be solved in half a minute. Or again a large number of simultaneous equations, as in a geodetic survey, could be solved in a few minutes: or the distribution of electric field round a charged conductor of specified shape.

The complete machine will naturally be costly; it is estimated that it may call for over £50,000, but probably not twice as much. A smaller one, containing the essential characteristics, could be constructed first, perhaps for a cost of £10,000, but its chief function would be to reveal some of the details of design that cannot be planned without trial, and its scope would be too limited to be worth constructing for its own sake. This would involve development work on delay lines and trigger circuits and this part of the work would be undertaken by the Post Office where facilities and specially trained staff exist, with the collaboration of Dr. Turing and his assistants. The Post Office are expecting to be able to profit by the development for their own purposes.

The small machine would not be a miniature substitute for the large machine but would later constitute a part of the full scale machine in due course. It is hoped that the complete machine can be constructed in three years and the financial requirement will be heaviest in the final year. It is proposed to proceed immediately, and with high priority, in the design and construction of this preliminary machine, but in doing so it is important to know that if it fulfils its promise there will be full backing for the greater sums required for the real operating machine. In view of its rapidity of action, and of the ease with which it can be switched over from one type of problem to another it is very possible that the one machine would suffice to solve all the problems that are demanded of it from the

Cartoon of Wilkinson and the Pilot ACE in 1952[93]

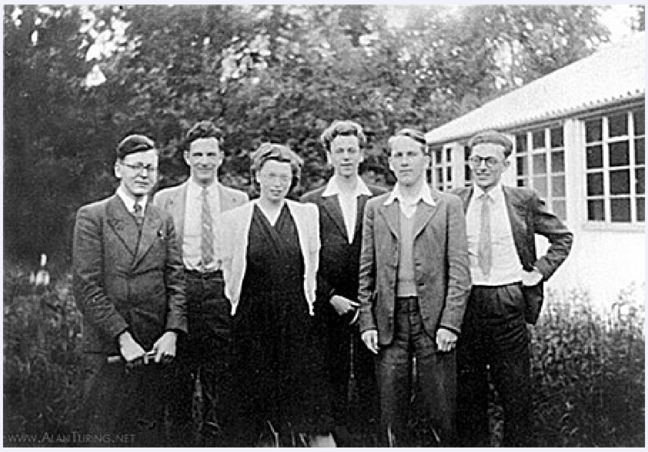
> **whole country. As far as can be estimated at the moment, two Scientific and one Experimental Officer will be required for this work in addition to Dr. Turing. Part of this staff would work at the Post Office Research Station during the development period. No estimate can as yet be given of the staff required to use the machine when completed. This staff would, however, in the main need to be in the Scientific Class since the machine itself will do the work of a very large number of Laboratory Assistants and Experimental Officers.**[303]

The Advisory Council of the DSIR agreed in May 1946 that 'in the event of the first-stage machine fulfilling expectations, they would be prepared to recommend further expenditure on a complete machine, bringing the total up to perhaps £100,000 in the next three years'.[304] It only remained to build the computer. However, as a result of ineffective management this would take much longer than anyone expected.

Cartoon showing the NPL main gate[94]

17. Turing Pioneers Computer Programming

In May 1946 James Wilkinson joined the NPL and was assigned to Turing on a half-time basis.[305] The ACE Section grew to a staff of three with the arrival of Michael Woodger later that year.[306] During 1946 Turing continually modified the design of the ACE. By the time of Wilkinson's arrival Turing had reached what he called 'Version V' of the design. (Woodger explains: 'My understanding is that the original report ['Proposed Electronic Calculator'] was not a Version as such but a general proposal. There is no trace of Versions I to IV; I assume they were sketches in Turing's possession, probably done between March and May 1946.'[307]) By the end of 1946 Turing had reached Version VII. From December 1946 to February 1947 Turing and Wilkinson gave a series of nine lectures on Versions V, VI and VII of the design (the lecture notes are reproduced in *Alan Turing's Automatic Computing Engine*).



The ACE group outside the NPL's Babbage Building in 1948. From the left: Jim Wilkinson, Stanley Gill. Betty Curtis, Gerry Alway, Mike Woodger, Henry Norton. Photo taken by Donald Davies.[95]

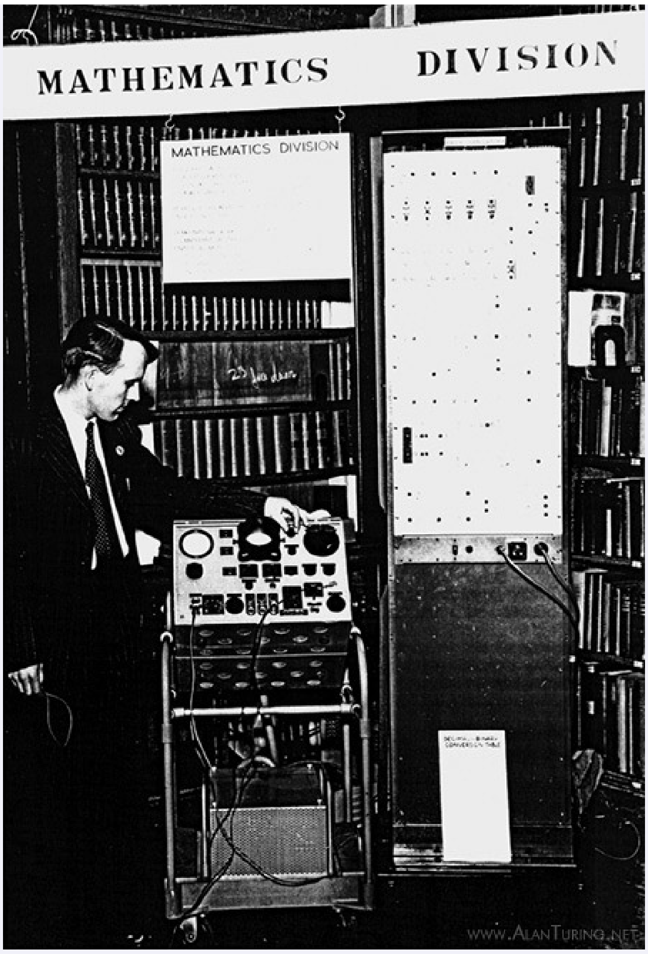
In 'Proposed Electronic Calculator' Turing had emphasized that work on writing programs (i.e. 'instruction tables') should 'start almost immediately', since the 'earlier stages of the making of instruction tables will have serious repercussions on the design' of the ACE. Moreover, this policy would, he said, 'avoid some of the delay between the delivery of the machine and the production of results'. Turing made this point again in a letter to Darwin: 'A large body of programming must be completed beforehand, if any serious work is to be done on the machine when it is made'.'[308] So it was that during 1946 Turing and Wilkinson, joined later by Woodger, pioneered the science of computer programming. An end-of-year report summarized their achievements:

> **Unless means can be found for the rapid preparation of problems in a form suitable for the machine the value of its high speed will largely be lost, though many other advantages would still remain. The first step, therefore, in planning such a machine, is to study the way in which programmes of work should be prepared. This has formed the main work of the A.C.E. section during the past year. It is intended to prepare the instructions to the machine on Hollerith cards, and it is proposed to maintain a**

library of these cards with programmes for standard operations. In setting up the machine to do a particular job all that will be necessary (instead of preparing the instructions in detail) will be to select a number of groups of standard instructions and to link them together with a few special cards. In planning the oganisation of the work on the machine it has become clear that a long and careful study of the many possible ways of setting out these instructions is essential, and even after more than a year of work on this problem, the final form is only now being reached. Apart from these general questions of organisation a number of basic instruction routines have been decided upon and prepared in detail. These are:-

Division.
Extracting square roots.
Indication of failures.
Testing the accuracy of a given table.
Exponential function.
Sine and cosine.
Logarithm.
Multiplication of complex numbers.
Formation of scalar product of vectors.
Formation of product of two matrices.
Solution of sets of linear equations.

Some work has also been done on developing known methods of solving both ordinary and partial differential equations in a form suitable for use on the A.C.E.[309]

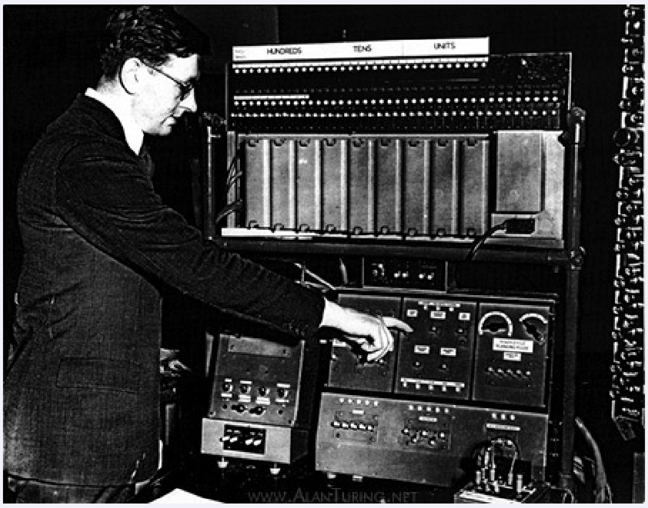


Michael Woodger and the ACE Simulator[96]

All this work was, of course, directed toward a machine that existed only on paper. The ACE Section, consisting only of three mathematicians, had no facilities to construct the computer.

18. First Attempt to Build the ACE: the Flowers Era

Turing knew that Flowers, who had designed and built Colossus, was uniquely qualified to undertake the construction of the ACE. Flowers was asked to organize the building of the ACE at his headquarters, the Post Office Research Station at Dollis Hill in North London (where Colossus was built).[310] He agreed. Early in 1946 Gordon Radley, Controller of Research at Dollis Hill (who knew about Colossus), wrote to Womersley to confirm the arrangement:



Jim Wilkinson at the control panel of the Pilot ACE[97]

Thank you for your letter received on Saturday morning. I had heard from Flowers that you were thinking of constructing an electronic numerical computing machine at the N.P.L. and share your hopes that it will far transcend in both facility and speed anything previously attempted. We should be very happy to co-operate, firstly by giving assistance with regard to the technical design of the machine and, later on when this has taken shape, by arranging to have it constructed for you within the Post Office organisation... .

With regard to the other aspect, that of

> time, we have very considerable arrears of work to overtake for our own Department. Some of it is most urgently required and the manpower position is difficult. I fully appreciate what you say, however, with regard to the fascinating nature of the task and the prestige value and it shall have the highest degree of priority possible in the circumstances.[311]

The 'arrears' mentioned by Radley were backlogs of urgent work on the national telephone system (at that time managed by the Post Office). Flowers could spare only two people to work on the ACE, Chandler and Coombs (who were later to build the **MOSAIC**). His section was, Flowers said, 'too busy to do other people's work'.[312] By the summer of 1946 warning bells had begun to ring at the NPL. In August Darwin observed that the Post Office was 'not in a position to plunge very deep' and by November he was expressing concern to Radley and others at the Post Office about the 'slow rate of progress' on the ACE.[313] Clearly it was time to make new arrangements. Initially the NPL persisted with the idea of placing a contract for the construction of the ACE with an outside organization. But this proved very difficult. Engineers experienced in the new art of digital electronics were scarce. Larger firms were 'likely to be too tied up with television and other consumer goods', and a suitable smaller company could not be found.[314]

T. H. Flowers[98]

The NPL also attemped to enlist the help of other public institutions. In August 1946 Darwin wrote to Sir Edward Appleton at the DSIR concerning the possibility of the **Telecommunications Research Establishment** at Malvern assisting in the construction of the ACE (see chapter 11 **The Manchester Computer**):

> As I told you Womersley was down at T.R.E. [Telecommunications Research Establishment] to see whether they could do any work about the A.C.E. machine. He tells me that it looks a most promising chance, and I think we should go ahead on it. Their lay-out for the job looks good, and I gather it appealed strongly to F. C. Williams as a job he would like to do, so that it should get a good chance. I am kicking myself for not having thought of it months ago as a possibility. ... It will be necessary to square T.R.E. officially over priorities, and on this I should like to bring high power to bear if necessary, because we have got a splendid chance of jumping in ahead of America.[315]

The Post Office Research Station at Dollis Hill, London. Here Flowers pioneered digital electronics and built Colossus.[99]

In October 1946 Darwin himself visited TRE on NPL business[316] and took the opportunity to bring up 'the possibility of F. C. Williams helping us on our ACE' (over two months after Womersley had made his initial approach—the pace of events was slow at the National Physical Laboratory).[317] Darwin met Williams, who demonstrated the principles of cathode ray tube memory[318] (see chapter 11 **The Manchester Computer**). Darwin realised that Williams' proposed memory was (in Darwin's own words) 'a most promising alternative ... more powerful than the mercury tubes, because its information would be available at need instead of only at fixed time intervals',[319] and Darwin 'hoped that considerable assistance could be obtained' from Williams.[320] Williams was sent a copy of Turing's 'Proposed Electronic Calculator' on Darwin's return to the NPL.[321] Not long afterwards

Darwin invited Williams, Uttley, and R. A. Smith (director of the Physics Department at TRE) to the NPL to meet with himself, Turing, and Womersley, in order to discuss 'in what way help could be given to the A.C.E. project'.[322] The meeting took place on 21 November 1946.[323] By that time, however, Williams had accepted the position of Professor of Electro-Technics at the University of Manchester, and shortly after the meeting Smith informed the NPL that, if Williams was to work on the ACE, it would be necessary to arrange a contract with the University.[324] Darwin offered a contract, but in the end Williams declined.[325] It was a pity—Williams would no doubt have got things moving on the hardware side. But on the other hand, Turing's design for the ACE was intimately based on the mercury delay line. An enforced collaboration between Turing and the pioneer of cathode ray tube memory might not have worked out well!

Freddie Williams[100]

The NPL also approached Maurice Wilkes, who was planning his own computer at the Cambridge Mathematical Laboratory (the **EDSAC**, which first ran in 1949). Douglas Hartree (Plummer Professor of Mathematical Physics at Cambridge and a member of the NPL Executive Committee) sounded him out and reported to the Executive Committee that Wilkes was 'prepared to give as much help as he could on the ACE'.[326] Wilkes 'had experience of making up [d]elay lines and would exchange information with Dr. Turing', Hartree said.[327] However, the chances of Turing's cooperating fruitfully with Wilkes may be judged by a memo from Turing to Womersley:

> I have read Wilkes' proposals for a pilot machine, and agree with him as regards the desirability of the construction of some such machine somewhere. I also agree with him as regards the suitability of the number of delay lines he suggests. The 'code' which he suggests is however very contrary to the line of development here, and much more in the American tradition of solving one's difficulties by means of much equipment rather than thought. I should imagine that to put his code (which is advertised as 'reduced to the simplest possible form') into effect would require a very much more complex control circuit than is proposed in our full-size machine. Furthermore certain operations which we regard as more fundamental than addition and multiplication have been omitted.
>
> It might be argued that if one is to have so little memory then it is necessary to have a complex control to make up. In so far as this is true I would say that it is an argument for either having no pilot model, or for not using it for serious problems. It is clearly rank folly to develop a complex control merely for the sake of the pilot model. I favour a model with a control of negligible size which can later be expanded if desired. Only test problems would be worked on the minimal machine.[328]

Flowers lecturing at the NPL in 1977[101]

By the beginning of 1947 there were no new initiatives to report. 'With regard to the design of actual equipment ... progress has been slow owing to staff shortage' was the lame summary in the end-of-year report for 1946.[329] The slow pace of the construction work at Dollis Hill was not entirely the fault of the Post Office. As previously mentioned, during 1946 Turing kept changing the logical design of the machine, and the NPL even considered using cathode ray tube memory in place of mercury delay lines—a change that would have meant most of the work done by Chandler and Coombs was wasted. Coombs described the situation from the engineers' point of view:

> **One of the problems was, I remember, that NPL kept on changing its ideas, and every time we went down there and said 'Right now! What do you want us to make?', we'd find that the last idea, that they gave us last week, was old hat and they'd got a quite different one, and we couldn't get a consolidated idea at all until eventually we dug our toes in and said 'Stop! Tell us what to make'.**

Maurice Wilkes with a set of delay lines from the EDSAC[102]

19. Second Attempt to Build the ACE: the Huskey Era and the Test Assembly

The situation improved when Harry Huskey—an engineer—arrived in Maths Division on a fixed-term contract. Huskey had worked on the ENIAC project and in 1946 was offered the Directorship of the EDVAC project, although complications prevented him from accepting.[330] Hartree, the ACE's guardian angel on the NPL Executive Committee, had met Huskey while visiting the ENIAC in the spring of 1946; in July Huskey received a telegram offering him a twelve-month visiting position at the NPL. (Hartree was one of the few outsiders to know about Colossus; shortly after the end of the war Newman had invited him to Bletchley Park to look at Colossus.[331]) Huskey began work in Maths Division on 4 January 1947.[332] A number of other new recruits joined the ACE Section during the course of 1947, in an expansion initiated by Turing (**Gerald Alway** in August, **Donald Davies** in September, **Henry Norton** in October, **Betty Curtis** in November).[333]

Harry Huskey[103]

Huskey soon suggested that the ACE Section itself make a start on constructing the computer and he proposed to Womersley that a small test assembly be built. With Womersley's blessing, Huskey, Wilkinson and Woodger began work. They planned to build a simplified form of Turing's Version V known as Version H (for 'Huskey'). The new machine—soon called the 'Test Assembly'—was to be housed in the Babbage Building, a short distance from Maths Division.[334] Womersley summarized the situation in a report written in the middle of 1947:

> **At the beginning of 1947 Dr. H. D. Huskey, a member of the team working on the EDVAC and ENIAC machines at the University of Pennsylvania, Philadelphia, joined the staff of the Mathematics Division for one year. In the Spring of 1947 it was decided that the Laboratory itself should undertake some experimental work and Dr. Huskey, with two assistants, began the collection of equipment with a view to constructing a small pilot model.**[335]

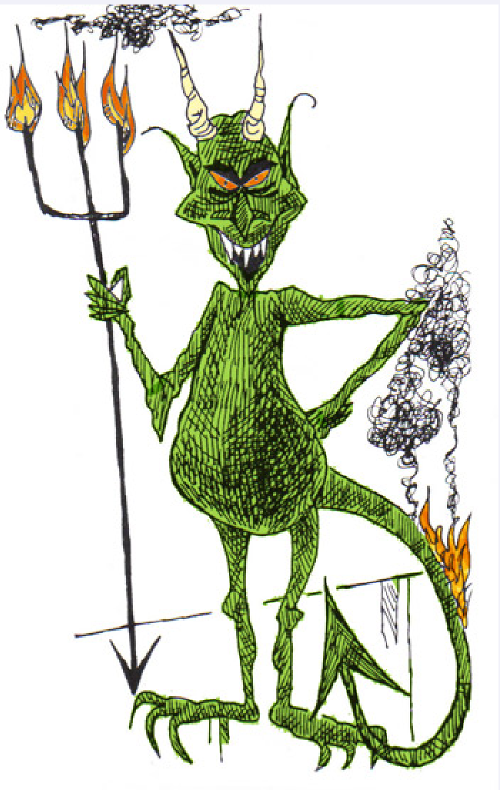
Turing was not in favour of this development. On the one hand the Test Assembly was to be a small computer in its own right, involving much more equipment than was strictly necessary to test the fundamentals of Turing's design, and yet on the other it fell far short of being the ACE, so possibly Turing saw Huskey's project as diverting effort from his own. According to Wilkinson, Turing 'tended to ignore the Test Assembly', simply 'standing to one side'.[336] Woodger described how he 'was writing a program for [Version H] when Turing came in ... looked over my shoulder and said, "What is this? What's Version H?". So I said, "It's Huskey's." "**WHAT!**" ... [T]here was a pretty good scene about that'.[337]

Huskey and the others pushed ahead with the Test Assembly. By about the middle of 1947, the NPL workshops were fabricating a mercury delay line to Huskey's specifications, valve types had been chosen and circuit block diagrams made, source and destination decisions had been taken, and programs were being written to check these decisions.[338] A main frame was built and construction of the plug-in chassis holding the circuitry was planned.[339] Huskey's first goal was to run a simple stored program using an absolute minimum of equipment and a single full-length delay line.[340] Then the group would develop a substantial computer capable of solving practical problems; this would contain approximately thirteen delay lines, and would involve punched card input and output and a hardware multiplier.[341] In October 1947 Womersley and E. C. Fieller expected—very optimistically—that the Test Assembly would 'be ready by the end of November'.[342] (Huskey said: 'I never hoped to have the Test Assembly working before I left in December. I certainly hoped the group would have it working in 1948.'[343]) Then, in what was one of the worst administrative decisions of the whole ACE saga, Darwin summarily stopped the work. 'Morale in the Mathematics Division collapsed', Huskey recalled.[344] The man behind Darwin's decision was Horace Augustus Thomas, head of the newly formed electronics group in the NPL's Radio Division.

20. Third Attempt to Build the ACE: the Disastrous Thomas Era

In January 1947 Turing had gone to the United States, visiting several of the groups that were attempting to build an electronic stored-program computer. In his report on this visit he wrote:

> **One point concerning the form of organisation struck me very strongly. The engineering development work was in every case being done in the same building with the more mathematical work. I am convinced that this is the right approach. It is not possible for the two parts of the organisation to keep in sufficiently close touch otherwise. They are too deeply interdependent. We are frequently finding that we are held up due to ignorance of some point which could be cleared up by a conversation with the engineers, and the Post Office find similar difficulty; a telephone conversation is seldom effective because we cannot use diagrams. Probably more important are the points which are misunderstood, but which would be cleared up if closer contact were maintained, because they would come to light in casual discussion. It is clear that we must have an engineering section at the ACE site eventually, the sooner the better, I would say.**[345]



It has not been possible to locate a photograph of Thomas[104]

Darwin decided that NPL's Radio Division was the best place for the experimental engineering work to be carried out. The minutes of the March 1947 meeting of the Executive Committee outlined the new arrangements:

> A.C.E. Director reported that he had had a meeting with members of the staff concerned. With a view to helping on progress with this machine it had been suggested that Dr. Thomas of Radio Division should be put in charge of the work of making by a suitable firm a prototype model. Dr. Thomas was very keen on electronic technique in industrial problems and he felt that the best way in which we could get progress would be to have a pre-prototype model started in Radio and Metrology workshops before approaching an outside firm. It was agreed that Dr. Thomas should prove a very suitable man for this work. In reply to a question from Professor Hartree, Director said that Metrology and Radio workshops could get on with the hardware part of the job straight away. Director stated that he had had a letter from the Post Office giving the position of their work which appeared to be most encouraging. Sir Edward Appleton said that he had heard from Dr. Radley that they were finding it difficult to keep to their delivery dates, and Dr. Radley will be seeing Director about this.[346]

The wheels of administration turned slowly and the idea of an in-house electronics section took several months to implement. At the end of April 1947 a joint minute to Darwin from Womersley and R. L. Smith-Rose, Superintendent of Radio Division, suggested that individuals be transferred from other Divisions to Radio Division in order to form 'the nucleus of a future electronics section':

> The present state of the project requires that the group should work together in one place as a whole in close contact with the planning staff in the Mathematics Division. The various parts are so interwoven that it is not practicable at present to farm out portions of the work to isolated groups. Our experience with the Post Office confirms this... . The re-allocation of staff within the Laboratory requires ... careful consideration, but if you are in agreement with our proposal, could you advise us as to what action could be taken in the immediate future.[347]

By August the months of 'careful consideration' finally came to an end and notes were sent out by E. S. Hiscocks (the Secretary of the NPL) to the Superintendents of various Divisions instructing them to transfer staff to Radio Division for a period of six months. Smith-Rose reported to Darwin: 'We are now in a position to commence experimental work in the development of the A.C.E. for Mathematics Division'.[348] Two members of Maths Division (Gill and Wise) were transferred, and Wilkinson, although not formally transferred, was expected by Womersley to work with Thomas's group for the first few months of the project.[349] **Edward Newman** joined the group at the beginning of September.[350] Recruited from EMI (Electric and Musical Industries) Research Laboratories, Newman would play an important role in the eventual construction of the Pilot ACE, as would **David Clayden**, who followed Newman from EMI later that month. Both Newman and Clayden were immersed in A. D. Blumlein's circuit techniques, which they brought with them from EMI (see *The Alan Blumlein Homepage* **<www.AlanTuring.net/blumlein>**).

In August 1947 a formal meeting was held to inaugurate the new state of affairs:

<u>A.C.E. Project</u>

A meeting was held in the large Conference Room on the 18th August to initiate the A.C.E. Project in the Radio Division. The following were present:-

Director
Secretary
Superintendent, Radio Division
Superintendent, Mathematics Division
Mr. F. M. Colebrook
Dr. A. M. Turing
Mr. J. W. Christelow
Dr. H. A. Thomas
Dr. F. Aughtie
Dr. H. Huskey
Mr. M. A. Wright
Mr. W. Wilson
Mr. A. F. Brown
Mr. R. G. Chalmers
Mr. B. J. Byrne
Mr. R. F. Braybrook
Mr. A. I. Williams

The Director opened the meeting by stating that this was the first time that a large team had been assembled at the Laboratory to initiate a research programme, and stressed the importance of the A.C.E. project. He pointed out that the Mathematics Division was the parent Department, and that they had, as it were, issued a contract to the Radio Division for the Development and completion of the machine.

Mr. Womersley followed by giving a historical summary commencing from the days of Babbage, and pointed out that the N.P.L. project, if successful, would give a machine much in advance of, and much quicker than, any of the American machines. It would afford a new approach to the problems of Mathematical [Physics] and would be of immense value to the country.[351]

Even before the inaugural meeting, trouble was brewing behind the scenes. On 12 August Hiscocks wrote to Darwin to alert him to what seemed to be empire-building on Thomas's part:

Thomas has apparently shown some signs of behaving as if he is starting up a new Division, and so as to allay certain qualms which both Smith-Rose and Womersley have, I think it would be better for it to be explained to the whole team that Mathematics Division is the parent Division, and the one which is to justify the financial outlay on this work; that the work is being put out on contract, as it were, to Radio Division, and

The legendary Alan Blumlein, a pioneer of digital electronics. Blumlein was killed in an air crash during the war while testing his new radar system for bomber aircraft.[105]

> **that Thomas's team is a part of Radio Division. I think, even if only for our own peace of mind, this is desirable, because Thomas has already shown some signs of wanting to set up a separate office, etc.**[352]

Blumlein in 1934[106]

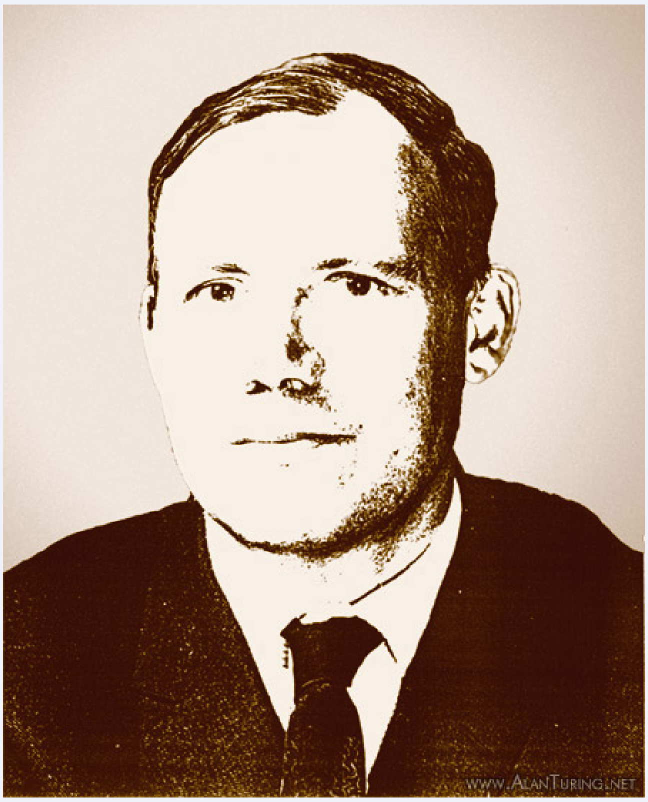
An unfortunate rivalry quickly sprang up between Thomas's group and the ACE Section in Maths Division. On 17 September Smith-Rose was sent an indignant letter complaining about a raid by Thomas's group on the ACE Section:

> **During Dr. Turing's and Dr. Huskey's absence on leave, most of the apparatus in our laboratory in Teddington Hall has, I believe, been removed to your Division. It would be of assistance in maintaining our inventory if we could have a list of what was, in fact, taken; we understood from Dr. Huskey that only two items were to be moved.**[353]

David Clayden[107]

Thomas the empire-builder soon petitioned Darwin to curtail the construction work in the ACE Section. Wilkinson said in an interview given in 1976: 'Thomas particularly didn't like ... the idea of this group in Mathematics Division ... working independently ... . Thomas persuaded the Director to lay it down that all work should be done in the Electronics Section and Darwin decreed that we should stop work on the Test Assembly'.[354]

The result was that the construction of the ACE drew almost to a standstill. Although Newman and Clayden were skilled in digital techniques, Thomas's group had much to learn. Thomas's own background was not in digital electronics at all but in radio and industrial electronics. The group 'began to develop their knowledge of pulse techniques', said Wilkinson, and 'for a while they just did basic things and became more familiar with the electronics they needed to learn to build a computer'.[355] Then, in February 1948, Thomas delivered another blow to the ACE project, resigning from the NPL to join Unilever Ltd (the manufacturers of 'Sunlight' soap). As Womersley summed up the situation shortly afterwards, hardware development was 'probably as far advanced 18 months ago'.[356]



Edward Newman[108]

It seems probable that, given better management at the NPL, a minimal computer based on Turing's Version V could have run a program during 1948. Turing first proposed an in-house electronics section at the NPL in his report of 3 February 1947. The Radio Division group could have been set up in six weeks rather than six months. Clearly the new electronics group should have joined forces with Huskey and the ACE Section to work on the Test Assembly. In August 1947 Womersley had pressed for this course of action, but Thomas threw a spanner in the works.[357] A rudimentary form of the Test Assembly might easily have run a trial program before the middle of 1948, becoming the world's first electronic stored-program digital computer.

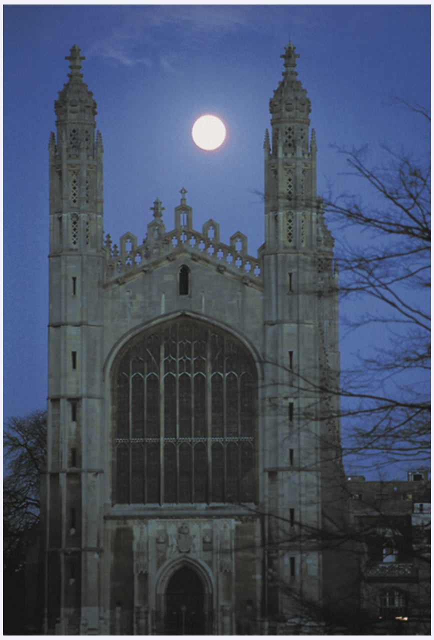
21. Turing Leaves the NPL

In mid-1947 Turing applied for a period of sabbatical leave to be spent at his Cambridge college. He proposed to pursue research on machine intelligence.[358] Darwin approved the request, saying in a letter to the DSIR:

> **As you know Dr. A. Turing ... is the mathematician who has designed the theoretical part of our big computing**

> engine. This has now got to the stage of ironmongery, and so for the time the chief work on it is passing into other hands. I have discussed the matter both with Womersley and with Turing, and we are agreed that it would be best that Turing should go off it for a spell.[359]

Turing left for Cambridge in the autumn of 1947.[360] He returned briefly to Mathematics Division the following spring (winning the three-mile run at the NPL Annual Sports Event).[361] Then, in May 1948, no doubt disheartened by the complete absence of progress on the construction of the ACE, he gave up his job at the NPL, accepting Newman's offer of a position at the Manchester Computing Machine Laboratory (see chapter 13 **Turing Joins the Manchester Project**). The struggle to bring the ACE into existence was now led by Wilkinson.



King's College, Cambridge. Photo © Andrew Pearce, **Fotogenix.co.uk**

22. Fourth Attempt to Build the ACE: the Wilkinson-Colebrook Era and the Pilot Model

Thomas was replaced by **Francis Morley Colebrook**, who in March 1948 was made head of the newly designated Electronics Section of Radio Division.[362] Colebrook at last got things moving. In 1976 Wilkinson recollected:

> I think quite soon [Colebrook] had an uncomfortable feeling that he'd inherited something which was in danger of floundering, and I had the same feeling back in Maths Division - I'd inherited this team from Turing and everybody was really a little bit demoralised by that time. And Colebrook rang me up and he came over to see me and had a chat about it and said he was not very happy about the position. And ... to my absolute astonishment he said: 'I've got a suggestion to make ... You chaps have learned a bit of electronics now ... What about coming over and joining us and the two groups working together?' ... I felt the whole thing was in such a mess it needed quite a decisive break in order to get it going... . Colebrook ... was a great diplomat ... and his goodwill was so evident to everybody that I do think he played a major part in making it possible for the two groups to go together.[363]

The combined group decided that the best course of action was to revive the Test Assembly, now described as a 'pilot model'.[364] (The similarity between the pilot model they now worked on and the out-of-favour Test Assembly was, Wilkinson said, 'more than ... it was diplomatic to say much about'.[365]) The ACE Section and the Electronics Section worked harmoniously together, and at the end of the year Womersley was able to report that '[v]ery good progress has been made'.[366] Huskey's approach to circuit design was replaced by the Blumlein approach which Newman and Clayden had brought from EMI. The group completely redesigned the electronics of the machine.

Soon the mathematicians from the ACE Section found themselves in a novel milieu. Woodger recalled: 'We set ourselves up in a little assembly line with ... a stack of components ... in front of us. Each of us had a soldering iron and we produced these things and passed them down the line. Oh, it was tremendous fun'.[367] Following a period of difficulty with the delay-line amplifiers at the end of 1949[368], the group finally tasted success. On 10 May 1950 the **Pilot Model ACE** ran its first program. Later known affectionately as 'Succ. Digs' (successive digits), the program turned on a row of 32 lights on the control panel at a speed determined by size of the number on the input switches.

The Pilot Model ACE was (in Colebrook's words) 'powerful computing equipment'.[369] Although the ultimate goal remained a large-scale ACE, Maths Division had been planning since 1948 to use the Pilot Model as a computing machine in its own right.[370] However, there was still considerable work to be done before the Pilot ACE could be handed over to Maths Division for customer service. Unreliable components were a problem and it was September 1950 before the machine had an error-free run of half an hour.[371] During 1951 the delay lines and the control of input and output were redesigned and the parallel multiplier was added.[372] By about the middle of 1951 the Pilot ACE was doing over fifty per cent of the computing work of Maths Division.[373] Nevertheless, by October 1951 it had still 'not yet been put into regular service', said Colebrook, 'and we have not yet built up an adequate "library" of generally useful sub-routines'.[374]

At the end of October 1951 the new Director of the NPL, Sir Edward Bullard, expressed the opinion that

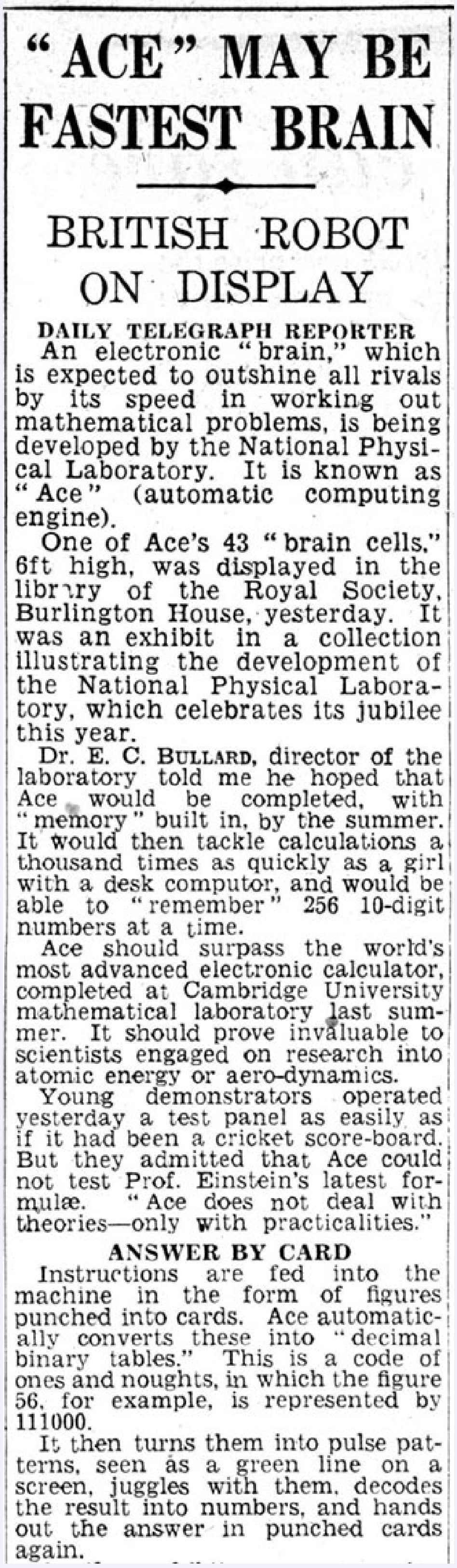
> most of the electronic machines, including our own, do not really work regularly and reliably. They have been very much over-advertised and there is a lot of work to be done before we have anything that is much use.[375]

Despite Bullard's pessimism, by February 1952 the Pilot ACE was reliable enough to be dismantled and transferred to Maths Division.[376] Colebrook wrote:

> Full operation was resumed within two weeks after the removal and has been continuous ever since, mainly on defence problems... . An analysis of the first eight weeks of operation, involving 370 power-on hours, gives the following figures:-

Routine testing and maintenance	92 hrs. 25%	
User training, programme testing, etc.	175 hrs. 47%	75%
Paid-for work[377]	103 hrs. 28%	

The Pilot ACE was a huge success. It was used both to carry out research in numerical analysis and to do paid work through Mathematics Division's scientific computing service. In 1954 alone the Pilot ACE earned the NPL £24,000 for over 80 jobs[378]—Turing's annual salary when he designed the ACE was £800.[379] In the course of its working life the machine earned approximately £100,000. The Pilot ACE remained in continuous service until replaced by the first **DEUCE** in 1955, by which time 'the amount of maintenance it require[d] preclude[d] it from being used economically as a computer'.[380]



"ACE" MAY BE FASTEST BRAIN

BRITISH ROBOT ON DISPLAY

DAILY TELEGRAPH REPORTER

An electronic "brain," which is expected to outshine all rivals by its speed in working out mathematical problems, is being developed by the National Physical Laboratory. It is known as "Ace" (automatic computing engine).

One of Ace's 43 "brain cells," 6ft high, was displayed in the library of the Royal Society, Burlington House, yesterday. It was an exhibit in a collection illustrating the development of the National Physical Laboratory, which celebrates its jubilee this year.

Dr. E. C. Bullard, director of the laboratory told me he hoped that Ace would be completed, with "memory" built in, by the summer. It would then tackle calculations a thousand times as quickly as a girl with a desk computor, and would be able to "remember" 256 10-digit numbers at a time.

Ace should surpass the world's most advanced electronic calculator, completed at Cambridge University mathematical laboratory last summer. It should prove invaluable to scientists engaged on research into atomic energy or aero-dynamics.

Young demonstrators operated yesterday a test panel as easily as if it had been a cricket score-board. But they admitted that Ace could not test Prof. Einstein's latest formulæ. "Ace does not deal with theories—only with practicalities."

ANSWER BY CARD

Instructions are fed into the machine in the form of figures punched into cards. Ace automatically converts these into "decimal binary tables." This is a code of ones and noughts, in which the figure 56, for example, is represented by 111000.

It then turns them into pulse patterns, seen as a green line on a screen, juggles with them, decodes the result into numbers, and hands out the answer in punched cards again.

The Daily Telegraph, 31 January 1950[109]

23. The DEUCE

Towards the end of 1948, the NPL's efforts to find an engineering company willing to assist with the ACE at last bore fruit. The minutes of the NPL Executive Committee for September 1948 report:

> **In connection with the A.C.E., members of Sir George Nelson's staff have visited the Laboratory to see the progress made and to discuss possible collaboration in the more detailed design and, later, the construction of the A.C.E.**[381]

Nelson, chairman of the English Electric Company, had been a member of the NPL Executive Committee since 1946 (and was present when Turing addressed the historic meeting of March 1946). Early in 1949 it was proposed that the NPL place a contract with English Electric:

> **A.C.E. Project.**
>
> **Present Position, and request for financial provision for a Study Contract to be placed with the English Electric Co. Ltd.**
>
> **... In order to expedite the construction of [the] pilot assembly and to make possible the construction of the final machine it is now proposed that a Study Contract be placed with the English Electric Co. Ltd. This will have two great advantages, first it will add to the labour force working on the construction of the pilot model, and should make possible its completion before the end of this year, and it will familiarise the engineers and the staff with the specialised requirements and the techniques involved. This educational period before they embark upon the construction of the final machine is very necessary in view of the novelty of the whole enterprise.**[382]

This contract was approved by the Treasury in May 1949.[383] It 'provided for members of the English Electric Company staff to work at the N.P.L., with N.P.L. staff involved'.[384] Engineers and wiremen from English Electric joined the NPL team to assist in the completion of the Pilot ACE.

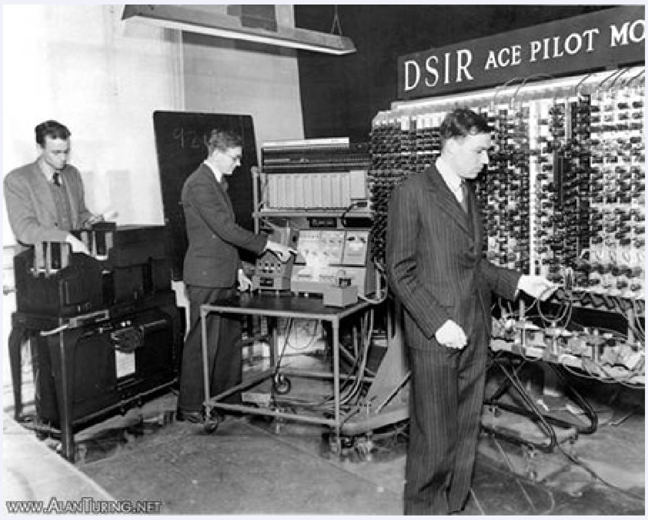
In 1951 an NPL memorandum set out a number of reasons for desiring to 'continue the collaboration with the E.E.Co.', including the following: 'The experience gained by the E.E.Co. would enable them to reproduce the A.C.E. or a similar machine for any subsequent home or foreign demand'.[385] By December 1951 arrangements for producing a commercial version of the Pilot ACE had been firmed up:

> **ACE - Arrangements with English Electric Co.**
>
> **... [I]t has been decided that the first move shall be the construction by the E.E. Co. of an "engineered version" of the present Pilot ACE. Simultaneously with this some of the detailed planning and design for the full-scale ACE will be undertaken.**[386]

A memo from Treasury noted approvingly that

> **These plans for the development of the A.C.E. represent a very favourable turn. English Electric (through Sir George Nelson) offered to take it upon themselves to**

The Pilot Model ACE in 1950, with (from left) Edward Newman, Francis Morley Colebrook, James Wilkinson, and Donald Davies[110]



The Pilot Model ACE in 1950, with Gerald Alway (left) at the Hollerith card input/output equipment, James Wilkinson (centre) at the control panel, and Edward Newman (right) at the main panel[111]

This DEUCE, photographed in 1956, was installed at the National Physical Laboratory in 1955[112]

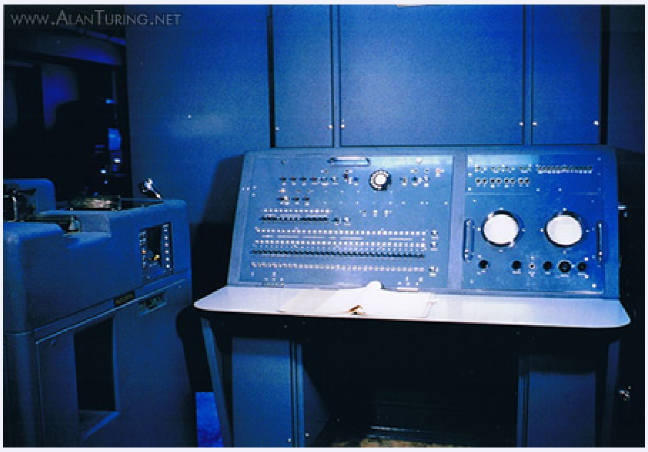
> construct a properly "engineered" version of the Pilot model at a cost to N.P.L. of no more than £5,000... . The likelihood is that [this] by no means represents the full economic cost. But Sir George Nelson is prepared to think in terms of such a figure because he would like to see English Electric getting into the field.[387]

The engineered version of the Pilot ACE was called—naturally enough—'the DEUCE' (Digital Electronic Universal Computing Engine). The first DEUCE to be produced was delivered to Maths Division in March 1955.[388] The DEUCE went on to become a cornerstone of the fledgling British computer industry.

This DEUCE, known as the UTECOM, was situated at the New South Wales University of Technology in Sydney, Australia (UTECOM stood for 'University of Technology Computer')[113]

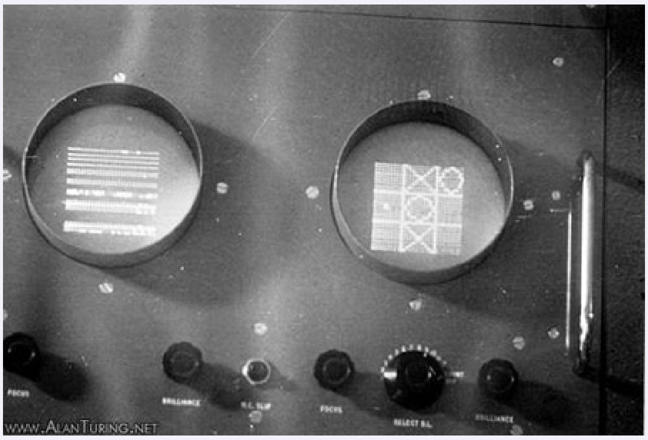
24. The Big ACE

Work began on a full-scale ACE in the autumn of 1954.[389] In 1956 J. R. Illingworth outlined the reasons for proceeding to this final stage of the project:



Control panel of the UTECOM. The topmost row of 13 white lights displayed the current instruction. The two circular monitors to the right displayed the contents of delay lines. The large device standing to the left of the control panel is the Hollerith card reader. Each program was entered in the form of a deck of many punched cards.[114]

> <u>ACE - Final Model</u>
>
> ... Experience had already shown ... that the DEUCE would not be an efficient proposition for more than four or five years since the speed and storage facilities required for this type of machine were becoming greater year by year. It was therefore decided about two years ago to commence work on an entirely new machine and this started in the Autumn of 1954... .
>
> The whole position, I think, may be summed up by saying that both the importance and the significance of this work has changed. In the early days when the project was envisaged it was not even known whether the conception of the ACE would lead to a research "toy" of any value, whereas events have proved it to be such a first class computing mechanism that we are under pressure from the Treasury and other departments to develop its use as rapidly as possible for work in office mechanisation. Moreover, whereas in the early days the project was regarded as an additional facet to the Laboratory's normal work, the whole of this field of work has become an inherent part of the Laboratory's programme.[390]



UTECOM playing noughts and crosses[115]

Built and housed at the NPL, the Big ACE was in operation by late 1958. Only one was made. Wilkinson, Clayden, Davies, Newman, and Woodger all contributed to the final design.[391] (English Electric played a part in 1954 and 1955 during the developmental stage, but at that point their contract with the NPL came to an end.[392]) With a clock speed of 1.5 MHz and containing some 6000 valves, the Big ACE filled a room the size of an auditorium.[393] The computer remained in service until 1967.

At a Press Day held in 1958 to inaugurate the Big ACE, A. M. Uttley (Superintendent of the Control Mechanisms and Electronics Division, as the Electronics Section had by then become) announced: 'Today, Turing's dream has come true'.[394] If so, it was a dream whose time had passed. The Big ACE was not the revolutionary machine that it would have been if completed six or seven years earlier. Not only did it employ valves in the era of the transistor, the designers also retained the by then outmoded mercury delay line memory proposed by Turing in 1945.[395] Nevertheless, the Big ACE was a fast machine with a large memory, and the decision to stick with the principles used in the Pilot ACE and the DEUCE was reasonable in the circumstances. In 1953 Colebrook urged that the proposed full-scale ACE 'be based on well proved components and techniques, even when revolutionary developments seem to be just around the corner'.[396] 'Otherwise the [Mathematics] Division will get nothing but a succession of pilot models', Colebrook argued.[397] As for speed, the machine's designers wrote in 1957: 'The ACE appears in fact to be about as fast as present-day parallel core-store computers' (magnetic core memory was the most advanced high-speed storage medium at that time).[398]

Work begins on the Big ACE. First the engineers constructed this mock-up of the layout[116]

A Simple Guide to ACE

One of the world's largest and fastest electronic computing machines - popularly called 'Electronic Brains' - has begun to operate at the National Physical Laboratory. Its name is ACE - and it can carry out any calculation process for which exact rules are known... .

ACE incorporates many unique design features. The operating "mechanism" consists of about 6,000 miniature electronic valves, arranged in an impressive array of 10 large cabinets. Each cabinet is fitted with an electrically operated rising door to give rapid access for fault finding. It has a cooling system of circulating air, with heat exchangers and a water cooler.

The numbers and instructions have 48 binary digits (equivalent to 14 decimal digits). The working store consists of 800 words, and the backing store of four magnetic drums will contain a total of 32,768 words.

Mercury delay lines and magnetic drums are used for the storage of numerical data and instruction sequences, and both punched card and magnetic tape equipment are provided for input and output.

The compact control desk has some 160 keys and 300 signal lamps, in addition to audible and visual displays of the computation. Nevertheless, most computations are carried out entirely by pushing one key - marked "Initial Input". This key causes punched cards to be read, which tell ACE what to do.

The most interesting mechanical assemblies in ACE are the four magnetic drums, entirely designed and constructed at N.P.L. The drums rotate at 12,000 r.p.m. so accurately that the arrival at a given point of a magnetic spot one hundredth of an inch in length, travelling at 200 miles per hour, is timed to a millionth of a second. The drums have unique rapidly moving recording heads and are only a part of the number store or "memory" of ACE. An idea of the speed of ACE

The Big ACE, November 1958. Raised panels expose the racks of chassis.[117]

can be gained from the fact that these drums are the slowest part of its number store!

Technical Notes

ACE has three forms of storage. The largest part of the store consists of four magnetic drums... . The access to these numbers is limited by the need to wait for the drum to revolve, and may take up to 7 milliseconds. These drums are used by the computer for the large mass of data that it may not want quickly.

For more rapid access, a mercury delay line store of 768 numbers is employed. The time required for access to these is up to one millisecond. This store is used for the program, but instructions are stored in such a way that no time is wasted in waiting for them.

The most rapid access store consists of short delay lines storing one, two or four numbers each. These are used for the small group of numbers that the computer is using for a short while.

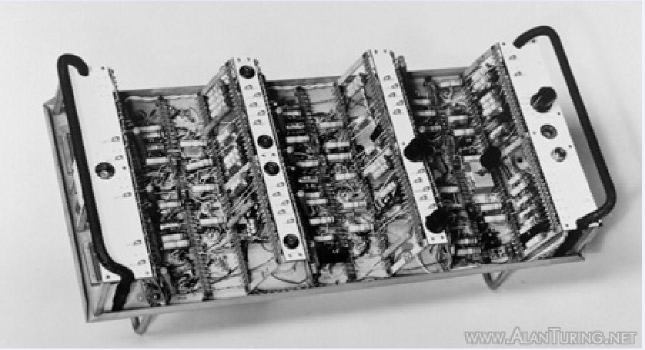
By good programming, the full advantages of the large store can be enjoyed, with a time of access not much greater than is given by the short delay lines.

The ACE instructions specify the addresses - the locations in the store - of two numbers to be operated on, the operation, and the addresses of the desired destination of the result and of the location of the next instruction. Thus four addresses are used, and all four accesses occur nearly simultaneously. [M]ultiplication and division occur in separate, autonomous devices, so that they can occur simultaneously with other operations.

In many cases, the computer will average 15,000 operations per second, each involving extracting two operands, storing the result and extracting the next instruction.

Input and output is by punched cards. Magnetic tapes will be fitted later, but will be used as an extension to the store. The input speed from cards will be 7000 binary digits per second, with a rate of 450 cards per minute punched in binary.[399]

Donald Davies, co-author of 'A Simple Guide to ACE'. Subsequently Davies invented 'packet switching', used in the ARPANET, forerunner of the Internet.[118]



Early chassis for the Big ACE, 1956[119]

25. Conclusion

Turing's **1936 paper** 'On Computable Numbers' gave the world the fundamental ingredients of the modern computer: the stored program concept and the concept of a universal machine.

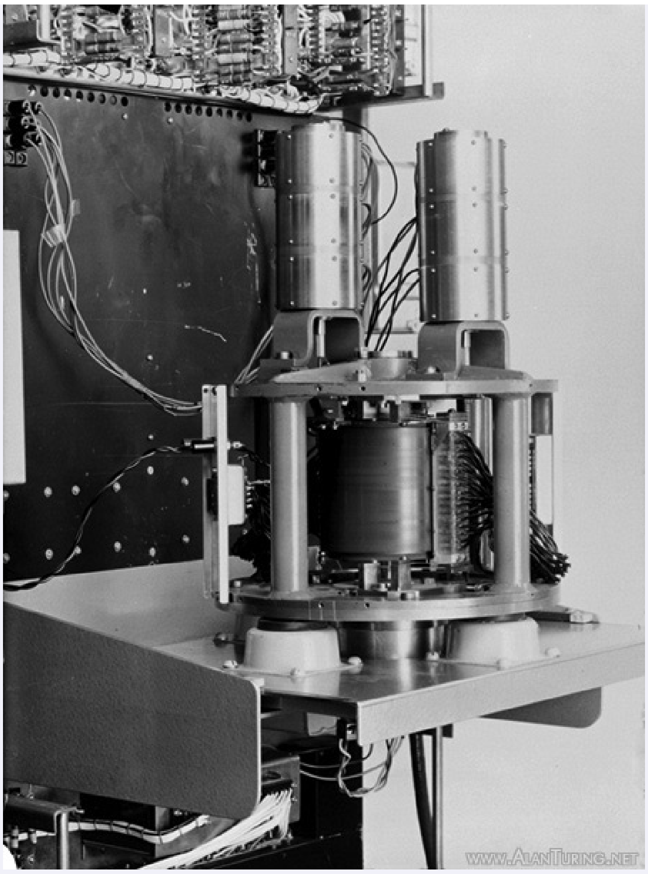
In the United States, **von Neumann** placed Turing's concept of a stored-program universal computer into the hands of the electronic engineers who would build the first American machines.

The 1936 paper profoundly influenced **Newman**, in whose

Computing Machine Laboratory at Manchester in 1948 the first functioning electronic stored-program computer came to life. Turing taught Kilburn, the designer of this machine, the fundamentals of computer architecture in lectures in 1946-7.

Turing's own sophisticated ACE design found commercial success in the **DEUCE**. Based on Version V of Turing's design, the DEUCE was a major workhorse of the first decades of the computer age. The first single-user, desk-side computer—the first personal computer—was also based on the ACE design (Huskey's **G15**). More yet would have flowed from Turing's ACE design had there been effective management at the National Physical Laboratory. Huskey's minimal ACE (the **Test Assembly**) might well have been the first electronic stored-program computer.

In addition to his remarkable theoretical and practical contributions to the development of the computer, Turing was the first pioneer of the areas of computing now known as **Artificial Intelligence** and **Artificial Life**.



128 track magnetic drum for the ACE Pilot Model, 1954[120]

Turing[121]

Alan Turing, Father of the Modern Computer

Part III

Turing on the ACE: The Complete Text of Turing's 'Proposed Electronic Calculator'

DESCRIPTIVE ACCOUNT

TECHNICAL PROPOSALS

TURING'S ORIGINAL FIGURES

Turing[118]

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37 Source: **The Turing Archive for the History of Computing**.

38 Source: From Warren S. McCulloch's 1962 essay, "Where is Fancy Bred?", collected in *Embodiments of Mind*.

39 Source: *Fortune Magazine*, June 1954.

40 Source: Arvin Calspan Advanced Technology Center; Hecht-Nielsen, R. *Neurocomputing* (Reading, Mass.: Addison-Wesley, 1990).

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64 Source: William Newman.

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Notes

1 With a huge debt of gratitude to html wizard Parker Bright for formatting the text and graphics.

This web-book draws extensively on material from our previous publications, including: Copeland, B. J. 'The Manchester Computer: A Revised History. *Part I* The Memory', and 'The Manchester Computer: A Revised History. *Part II* The Baby Machine', *IEEE Annals of the*

A Revised History: *Part II The Baby Machine*', *IEEE Annals of the History of Computing*, vol. 33 (2011), pp. 4-21 and 22-37; Copeland, B. J., Proudfoot, D. 'Turing's Test: A Philosophical and Historical Guide', in Epstein, R., Roberts, G. and Beber, G. (eds), *Parsing The Turing Test* (Berlin: Springer, 2008); Copeland, B. J., Proudfoot, D. 'Artificial Intelligence: History, Foundations, and Philosophical Issues',

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9 Copeland, B. J. *The Essential Turing* (Oxford and New York: Oxford University Press, 2004), chs 5 and 6.

10 A memo, 'Naval Enigma Situation', dated 1 November 1939 and signed by Knox, Twinn, Welchman, and Turing, said: 'A large 30 enigma bomb [sic] machine, adapted to use for cribs, is on order and parts are being made at the British Tabulating Company'. (The memo is in the National Archives/Public Record Office, Kew, Richmond, Surrey; document reference HW 14/2.)

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27 Memo from Turing to Womersley, c. December 1946 (in the Woodger Papers, National Museum of Science and Industry, Kensington, London (catalogue reference M15/77); a digital facsimile is in *The Turing Archive for the History of Computing* **<http://www.AlanTuring.net/turing_womersley_cdec46>**). NPL documents are © Crown copyright and extracts are reproduced by permission of the Controller of HMSO.

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35 Figure 3 is on p. 198 of the reprinting of the 'First Draft' in Stern, N. *From ENIAC to UNIVAC: An Appraisal of the Eckert-Mauchly Computers* (Bedford, Mass.: Digital Press, 1981).

36 *Evening News*, 23 December 1946. The cutting is among a number placed by Sara Turing in the Modern Archive Centre, King's College, Cambridge (catalogue reference K 5).

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38 'I know that von Neumann was influenced by Turing ... during his Princeton stay before the war', said Stanislaw Ulam (in interview with Evans in 1976, 'The Pioneers of Computing: an Oral History of Computing' (London: Science Museum; © Board of Trustees of the Science Museum. Audiotape of interview, supplied to Copeland by the archives of the London Science Museum in 1995; transcribed by Copeland 1997).) When Ulam and von Neumann were touring in Europe during the summer of 1938, von Neumann devised a mathematical game involving Turing-machine-like descriptions of numbers (Ulam reported by William Aspray in his *John von Neumann and the Origins of Modern Computing* (Cambridge, Mass.: MIT Press, 1990), pp. 178, 313). The word 'intrigued' is used in this connection by von Neumann's friend and colleague Herman Goldstine in his *The Computer from Pascal to von Neumann* (Princeton: Princeton University Press, 1972), p. 275.

39 Letter from Frankel to Brian Randell, 1972 (in Randell's 'On Alan Turing and the Origins of Digital Computers', in Meltzer, B., Michie, D. (ed.) *Machine Intelligence 7* (Edinburgh: Edinburgh University Press, 1972)). (Copeland is grateful to Randell for giving him a copy of the letter.)

40 Burks (a member of the ENIAC group) summarized matters thus in his 'From ENIAC to the Stored-Program Computer: Two Revolutions in Computers' (in Metropolis, N., Howlett, J., Rota, G. C. (ed.) *A History of Computing in the Twentieth Century* (New York: Academic Press, 1980), p. 312):

> Pres [Eckert] and John [Mauchly] invented the circulating mercury delay line store, with enough capacity to store program information as well as data. Von Neumann created the first modern order code and worked out the logical design of an electronic computer to execute it.

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46 The first papers in the series were the 'First Draft of a Report on the EDVAC' (von Neumann, 1945), and 'Preliminary Discussion of the Logical Design of an Electronic Computing Instrument' (Burks, Goldstine, von Neumann, 1946).

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53 'Engineer-in-Chief's Report on the Work of the Engineering Department for the Year 1 April 1952 to 31 March 1953', Post Office Engineering Department (The Post Office Archive, London).

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57 The 'Engineer-in-Chief's Report on the Work of the Engineering Department for the Year 1 April 1954 to 31 March 1955' stated 'The digital computer "Mosaic" has been completed and handed over to the Ministry of Supply'.

Ministry of Supply'.

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Flowers' work at Bletchley led, via Newman's desire to put the concept of the stored-program universal computing machine into practice, to the Manchester Computing Machine Laboratory and the Manchester Mark I computer' (pp. 366, 369).

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198 Newman, M. H. A. 'General Principles of the Design of All-Purpose Computing Machines', *Proceedings of the Royal Society of London*, Series A, vol. 195 (1948), pp. 271-274; the quotation is from p. 273.

199 Newman in interview with Evans ('The Pioneers of Computing: An Oral History of Computing' (London: Science Museum)). Transcription by Copeland.

200 Newman, M. H. A. 'General Principles of the Design of All-Purpose Computing Machines', *Proceedings of the Royal Society of London*, Series A, vol. 195 (1948), pp. 271-274; the quotation is from 273-4.

201 See also the Section on Newman in Copeland, B. J. 'A Lecture and Two Radio Broadcasts on Machine Intelligence by Alan Turing', in *Machine Intelligence 15* (1999), pp. 454-457; Copeland, B. J. 'Colossus and the Dawning of the Computer Age', in Erskine, R., Smith, M. (eds) *Action This Day* (London: Bantam Books, 2001); and Copeland, B. J. *The Essential Turing* (Oxford and New York: Oxford University Press, 2004), pp. 371ff.

202 Huskey's report is now published as chapter 23 ('The State of the

202 Huskey's report is now published as chapter 23 ('The State of the Art in Electronic Digital Computing in Britain and the United States') of Copeland, B. J. *Alan Turing's Automatic Computing Engine* (Oxford and New York: Oxford University Press, 2005).

203 As far as we know, Williams' historic tape-recorded statements that 'neither Tom Kilburn nor I knew the first thing about computers when we arrived in Manchester University' and that 'Newman explained the whole business of how a computer works to us' first appeared in print in the *Times Literary Supplement* in our 1998 article 'Enigma Variations', published on the 50th anniversary of the Manchester Baby (*TLS*: 'Information Technology', 3 July 1998, p. 6). In this article we said: 'Not that history has been particularly kind either to Newman or to Turing. Their logico-mathematical contributions to the triumph at Manchester have been neglected, and the Manchester machine is nowadays remembered as the work of Williams and Kilburn.' We explained that, contrary to the received history of the Manchester computer, Newman had played a substantial role; and we also emphasised the importance of Colossus in the history of the Manchester computer: 'Flowers's racks of high-speed electronic digital equipment led Newman to think seriously about building an electronic universal Turing machine. The war over, he accepted a chair at Manchester [and] applied to the Royal Society for a grant to establish his Computing Machine Laboratory.'

204 Letter from Williams to Randell, 1972 (in Randell, B. 'On Alan Turing and the Origins of Digital Computers', in Meltzer, B., Michie, D. (ed.) *Machine Intelligence 7* (Edinburgh: Edinburgh University Press, 1972); the letter is on p. 9).

205 Williams in interview with Evans in 1976 ('The Pioneers of Computing: An Oral History of Computing' (London: Science Museum)). Transcription by Copeland.

206 Kilburn, T. 'From Cathode Ray Tube to Ferranti Mark I', *Computer Resurrection*, vol. 1 (1990), pp. 16-20.

207 Kilburn in interview with Copeland (July 1997).

208 'The Turing-Wilkinson Lecture Series (1946-7)', in Copeland, B. J. *Alan Turing's Automatic Computing Engine* (Oxford and New York: Oxford University Press, 2005). See also Copeland, B. J. 'The Turing-Wilkinson Lecture Series on the Automatic Computing Engine', in Furukawa, K., Michie, D., Muggleton, S. (eds) *Machine Intelligence 15* (Oxford and New York: Oxford University Press, 1999), pp. 381-444.

209 Letter from Maurice Wilkes to Copeland (11 April 1997); Womersley's handwritten notes concerning the arrangements for the lectures (Woodger Papers, catalogue reference M15; digital facsimiles are in *The Turing Archive for the History of Computing* **<http://www.AlanTuring.net/womersley_notes_22nov46>**). See also the Introduction to 'The Turing-Wilkinson Lecture Series (1946-7)' in Copeland, B. J. *Alan Turing's Automatic Computing Engine* (Oxford and New York: Oxford University Press, 2005), pp. 459-464.

210 Bowker, G., Giordano, R. 'Interview with Tom Kilburn', *Annals of the History of Computing*, vol. 15 (1993), pp. 17-32; see p. 19.

211 Letter from Brian Napper to Copeland (16 June 2002).

212 Bowker, G., Giordano, R. 'Interview with Tom Kilburn', *Annals of the History of Computing*, vol. 15 (1993), pp. 17-32; the quotation is from p. 19. (Copeland is grateful to Napper for drawing this passage to his attention, in correspondence during 2002.)

213 Kilburn, T. 'A Storage System for Use with Binary Digital Computing Machines', Report for TRE, 1 December 1947 (National Archive for the History of Computing, University of Manchester; a retyped version, complete with editorial notes, is at **<http://www.computer50.org/kgill/mark1/report1947.html>**).

214 Kilburn, T. 'The University of Manchester Universal High-Speed Digital Computing Machine', *Nature*, vol. 164, no. 4173 (1949), pp. 684-7; the quotation is from p. 687.

215 Williams in interview with Evans in 1976 ('The Pioneers of Computing: An Oral History of Computing' (London: Science Museum)). Transcription by Copeland (1997).

216 Kilburn, T. 'A Storage System for Use with Binary Digital Computing Machines', Report for TRE, 1 December 1947 (National Archive for the History of Computing, University of Manchester; a retyped version, complete with editorial notes, is at **<http://www.computer50.org/kgill/mark1/report1947.html>**).

217 This paragraph summarises section 1.4 of Kilburn, T. 'A Storage System for Use with Binary Digital Computing Machines', Report for TRE, 1 December 1947. See also Napper, B. 'Covering Notes for Tom Kilburn's 1947 report to TRE' **<http://www.computer50.org/kgill/mark1/report1947cover.html>**. We are indebted to Napper for helpful correspondence.

218 Ibid.

219 The terms 'decentralised' and 'centralised' were introduced in a letter about Manchester computer architecture from Good to Newman (8 August 1948), in Good, I. J. 'Early Notes on Electronic Computers' (unpublished, compiled in 1972 and 1976; a copy is in the University of Manchester National Archive for the History of Computing, MUC/Series 2/a4), pp. 63-4.

220 One feature of Kilburn's design that was not found in the ACE is his distinction between the 'instruction store' and the 'number store'; as Kilburn pointed out, however, the 'separation of the main store into number and order stores is purely artificial, and has been done to simplify the description' (Kilburn, T. 'A Storage System for Use with Binary Digital Computing Machines', Report for TRE, 1 December 1947, section 1.4).

221 'The Turing-Wilkinson Lecture Series (1946-7)', in Copeland, B. J. *Alan Turing's Automatic Computing Engine* (Oxford and New York: Oxford University Press, 2005); the quotation is from pp. 477, 478, 489.

222 Bowker, G., Giordano, R. 'Interview with Tom Kilburn', *Annals of the History of Computing*, vol. 15 (1993), pp. 17-32; the quotation is from p. 19.

223 Williams, F. C., Kilburn, T. 'The University of Manchester Computing Machine', in Bowden, B. V. ed. *Faster Than Thought* (London: Sir Isaac Pitman & Sons, 1953); see p. 118.

224 There is a detailed analysis of Eckert's role, as well as of the roles of other US pioneers of cathode ray tube memory such as Robert McConnell, in Copeland's 'The Manchester Computer: A Revised History. *Part I* The Memory', *IEEE Annals of the History of Computing*, vol. 33 (2011), pp. 4-21.

225 Kilburn in interview with Copeland (July 1997).

226 Letter from Tootill to Copeland (18 April 2001).

227 Letter from Tootill to Copeland (16 May 2001).

228 Letter from Williams to Randell, 1972 (in Randell, B. 'On Alan Turing and the Origins of Digital Computers', in Meltzer, B., Michie, D. (ed.) *Machine Intelligence 7* (Edinburgh: Edinburgh University Press, 1972); the letter is on p. 9).

229 Good, I. J. 'Early Notes on Electronic Computers', pp. vii, ix.

230 Letter from Rees to Copeland (2 April 2001).

231 Newman, W. 'Max Newman: Mathematician, Codebreaker and Computer Pioneer', in Copeland, B. J. et al. *Colossus: The Secrets of Bletchley Park's Codebreaking Computers* (Oxford and New York: Oxford University Press, 2006, new edition 2010).

232 Burks, A. W., Goldstine, H. H., von Neumann, J. 'Preliminary Discussion of the Logical Design of an Electronic Computing Instrument', Institute for Advanced Study, 28 June 1946 (reprinted in Vol. 5 of Taub, A. H. ed. *Collected Works of John von Neumann* (Oxford: Pergamon Press, 1961)). The Manchester copy of the report (Copy #54) is in the National Archive for the History of Computing, University of Manchester.

233 Good, I. J. 'Early Notes on Electronic Computers', pp. iii, viii.

234 Good, I. J. four sheets of notes, c. 16 February 1947, in Good, 'Early Notes on Electronic Computers', pp. 2-5.

235 The quotation is from Good's revised typescript of his acceptance speech delivered on 15 October 1998, p. 31. (Good sent Copeland a copy of this typescript in January 1999.)

236 Good, I. J. 'Early Notes on Electronic Computers', p. iv. See also Croarken, M. 'The Beginnings of the Manchester Computer Phenomenon: People and Influences', *IEEE Annals of the History of Computing*, vol. 15 (1993), pp. 9-16; Lee, J. A. N. *Computer Pioneers* (Los Alamitos: IEEE Computer Society Press, 1995), p. 744.

237 Good, I. J. 'The Baby Machine', 4 May 1947, p. 1. In an earlier note ('Fundamental Operations', circa 16 February 1947; in Good's 'Early Notes on Electronic Computers') Good had listed a larger and considerably more complicated set of basic operations. These included multiplication, division, |x|, two forms of conditional transfer of control, and an instruction transferring the number in the accumulator to the 'house number in' house x. These instructions were intended for a machine with two instructions per word (the Williams and Kilburn Baby had only one instruction per word).

238 Burks, A. W., Goldstine, H. H., von Neumann, J. 'Preliminary Discussion of the Logical Design of an Electronic Computing Instrument', section 6.6.

239 Burks, A. W., Goldstine, H. H., von Neumann, J. 'Preliminary Discussion of the Logical Design of an Electronic Computing Instrument', Table 1 and section 6. The operation 'transfer the number in A to R' is discussed in 6.6.3, where it is pointed out that this operation can be made basic at the cost of 'very little extra equipment'. The two shift operations L and R are introduced in 6.6.7.

240 This was established (by Copeland) by comparing the Baby's six basic operations given by Williams and Kilburn in their 1948 paper in *Nature* with the instructions in Good's May 1947 set. The detailed comparison is set out in the sidebar on p. 26 of Copeland's 'The Manchester Computer: A Revised History. *Part II* The Baby Machine', *IEEE Annals of the History of Computing*, vol. 33 (2011), pp. 22-37. (See also Williams, F. C., Kilburn, T. 'Electronic Digital Computers',

(See also Williams, F. C., Kilburn, T. 'Electronic Digital Computers', *Nature*, vol. 162, no. 4117 (1948), p. 487; Williams, F. C. 'Early Computers at Manchester University', *The Radio and Electronic Engineer*, vol. 45 (1975), pp. 327-331; see pp. 329-30.)

241 David Anderson argued that the Baby was based on a different instruction set, written down by Good in February 1947 and mentioned in the previous footnote (Anderson, 'Was the Manchester Baby Conceived at Bletchley Park?', University of Portsmouth Research Report number UoP-HC-2006-001, published on the internet in 2006), but this is incorrect. It was the May instruction set, not the more complex February set, that Kilburn received from Good and simplified to 5 instructions (plus 'stop'). The February instruction set, unlike the May set, was intended for a machine with two instructions per word. Good made it completely clear that it was the May set, not the February set, that he suggested in response to Kilburn's request 'for a small number of basic instructions' (Good, 'Early Notes on Electronic Computers', p. iv). (The February instruction set is presented in Appendix 2 of Anderson's 'Was the Manchester Baby Conceived at Bletchley Park?', pp. 46-48; there is no mention of Good's May 1947 note 'The Baby Machine' nor of the instruction set that it contained.)

242 Good, I. J. 'The Baby Machine', 4 May 1947, p. 1; Good's symbolic expression of the operations uses the notation 'A' (Accumulator) and 'C' (Control). See also p. 2 of Good's 'Early Notes on Electronic Computers', headed 'Abbreviations'.

243 Kilburn in interview with Copeland (July 1997).

244 Kilburn in interview with Copeland (July 1997).

245 Kilburn, T. 'A Storage System for Use with Binary Digital Computing Machines', Report for TRE, 1 December 1947, Bibliography.

246 'Report by Professor M. H. A. Newman on Progress of Computing Machine Project', Minutes of the Council of the Royal Society, 13 January 1949 (in the archives of the Royal Society of London).

247 Huskey, H. D. 'The State of Computing in Britain and the U.S.', National Physical Laboratory, 1947. In Copeland, B. J. *Alan Turing's Automatic Computing Engine* (Oxford and New York: Oxford University Press, 2005); the quotation is from p. 536.

248 See especially section 5.5 of Burks, Goldstine, and von Neumann, 'Preliminary Discussion of the Logical Design of an Electronic Computing Instrument'.

249 Williams, F. C., Kilburn, T. 'The University of Manchester Computing Machine', in Bowden, B. V. ed. *Faster Than Thought* (London: Sir Isaac Pitman & Sons, 1953); Williams, F. C., Kilburn, T., Tootill, G. C. 'Universal High-Speed Digital Computers: A Small-Scale Experimental Machine', *Proceedings of the Institution of Electrical Engineers*, vol. 98 (1951), pp. 13-28.

250 As is made clear by a comparison of section 6.4 of Burks, Goldstine, and von Neumann, 'Preliminary Discussion of the Logical Design of an Electronic Computing Instrument' with pp. 118-119 of Williams, F. C., Kilburn, T. 'The University of Manchester Computing Machine', in Bowden, B. V. ed. *Faster Than Thought* (London: Sir Isaac Pitman & Sons, 1953) and pp. 17-18 of Williams, F. C., Kilburn, T., Tootill, G. C. 'Universal High-Speed Digital Computers: A Small-Scale Experimental Machine', *Proceedings of the Institution of Electrical Engineers*, vol. 98 (1951), pp. 13-28.

251 'Preliminary Discussion of the Logical Design of an Electronic Computing Instrument', section 4.3.

252 Kilburn in interview with Copeland (July 1997).

253 Huskey, H. D. 'The State of Computing in Britain and the U.S.', National Physical Laboratory, 1947. In Copeland, B. J. *Alan Turing's Automatic Computing Engine* (Oxford and New York: Oxford University Press, 2005); the quotation is from p. 535.

254 Williams, F. C., Kilburn, T. 'A Storage System for Use with Binary Digital Computing Machines', *Proceedings of the Institution of Electrical Engineers*, vol. 96 (1949), pp. 81-100.

255 Bigelow, J. 'Computer Development at the Institute for Advanced Study', in Metropolis, N., Howlett, J., Rota, G. C. (ed.) *A History of Computing in the Twentieth Century* (New York: Academic Press, 1980), p. 304.

256 Goldstine, H. H. *The Computer from Pascal to von Neumann* (Princeton: Princeton University Press, 1972), p. 310.

257 Bigelow, J. 'Computer Development at the Institute for Advanced Study', in Metropolis, N., Howlett, J., Rota, G. C. (ed.) *A History of Computing in the Twentieth Century* (New York: Academic Press, 1980), p. 304; Goldstine, H. H. *The Computer from Pascal to von Neumann* (Princeton: Princeton University Press, 1972), p. 310.

258 Bigelow, J. 'Computer Development at the Institute for Advanced Study', p. 304.

259 Bigelow, J. 'Computer Development at the Institute for Advanced Study', in Metropolis, N., Howlett, J., Rota, G. C. (ed.) *A History of Computing in the Twentieth Century* (New York: Academic Press, 1980), pp. 305-6.

260 Goldstine, H. H. *The Computer from Pascal to von Neumann* (Princeton: Princeton University Press, 1972), p. 96.

261 Goldstine, H. H. *The Computer from Pascal to von Neumann* (Princeton: Princeton University Press, 1972), p. 265.

262 Kilburn, T. 'The University of Manchester Universal High-Speed Digital Computing Machine', *Nature*, vol. 164, no. 4173 (1949), pp. 684-7; see p. 687.

263 Kilburn in interview with Copeland (July 1997).

264 Goldstine, H. H. *The Computer from Pascal to von Neumann* (Princeton: Princeton University Press, 1972), p. 308.

265 Robin Gandy in interview with Copeland (October 1995).

266 Letter from Williams to Randell, 1972 (in Randell, B. 'On Alan Turing and the Origins of Digital Computers', in Meltzer, B., Michie, D. (ed.) *Machine Intelligence 7* (Edinburgh: Edinburgh University Press, 1972); the letter is on p. 9).

267 Turing, A. M. 'Programmers' Handbook for Manchester Electronic Computer', Computing Machine Laboratory, University of Manchester (no date, c. 1950); a digital facsimile is in *The Turing Archive for the History of Computing* **<http://www.AlanTuring.net/programmers_handbook>**.

268 This fact was first publicised in Lavington, S. H. *A History of Manchester Computers* (Manchester: NCC Publications, 1975), p. 20 (although the date of the first UNIVAC is given there as June 1951). Martin Campbell-Kelly provides an excellent account of the Mark I

(together with biographical information on Newman, Williams, Kilburn, and other Manchester figures) in his 'Programming the Mark I: Early Programming Activity at the University of Manchester', *IEEE Annals of the History of Computing*, vol. 2 (1980), pp. 130-168.

269 Stern, N. 'The BINAC: A Case Study in the History of Technology' *Annals of the History of Computing*, vol. 1 (1979), pp. 9-20 (p. 17); Stern, N. *From ENIAC to UNIVAC: An Appraisal of the Eckert-Mauchly Computers* (Bedford, Mass.: Digital, 1981), p. 149.

270 Letter from Williams to Randell, 1972 (in Randell, B. 'On Alan Turing and the Origins of Digital Computers', in Meltzer, B., Michie, D. (ed.) *Machine Intelligence 7* (Edinburgh: Edinburgh University Press, 1972); the letter is on p. 9).

271 Williams in interview with Evans in 1976 ('The Pioneers of Computing: AnOral History of Computing' (London: Science Museum)), transcription by Copeland.

272 Williams, F. C., Kilburn, T. 'The University of Manchester Computing Machine', in *Review of Electronic Digital Computers: Joint AIEE-IRE Computer Conference* (New York: American Institute of Electrical Engineers, 1952), p. 61.

273 Flowers, T. H. 'Colossus', in Copeland, B. J. et al. *Colossus: The Secrets of Bletchley Park's Codebreaking Computers* (Oxford and New York: Oxford University Press, 2006, 2010), p. 100.

274 Kilburn in interview with Copeland (July 1997); Tootill, G. C. 'Informal Report on the Design of the Ferranti Mark I Computing Machine', November 1949 (National Archive for the History of Computing, University of Manchester).

275 Letter from Tootill to Copeland (18 April 2001).

276 Kilburn in interview with Copeland (July 1997).

277 Wilkinson, J. H. 'Turing's Work at the National Physical Laboratory and the Construction of Pilot ACE, DEUCE, and ACE', in Metropolis, N., Howlett, J., Rota, G. C. (ed.) *A History of Computing in the Twentieth Century* (New York: Academic Press, 1980), p. 104; Copeland, B. J. *Alan Turing's Automatic Computing Engine* (Oxford and New York: Oxford University Press, 2005), pp. 241-2.

278 Turing, A. M. 'Checking a Large Routine', *Report of a Conference on High Speed Automatic Calculating Machines* (Mathematical Laboratory, University of Cambridge, 1950).

288 Woodger in interview with Copeland (June 1998).

289 'Superintendent of the Mathematics Division', National Physical Laboratory, report E. 849, 28 September 1944 (NPL library; a digital facsimile is in *The Turing Archive for the History of Computing* **<http://www.AlanTuring.net/womersley_appointment>**).

290 'Research Programme for the Year 1945-46', National Physical Laboratory, October 1944, items 6502, 6502.1, 6502.2 (NPL library; a digital facsimile is in *The Turing Archive for the History of Computing* **<http://www.AlanTuring.net/research_programme_1945-46>**).

291 'Report of Interdepartmental Technical Committee on a Proposed Central Mathematical Station', Department of Scientific and Industrial Research, 3 April 1944 (NPL library; a digital facsimile is in *The Turing Archive for the History of Computing* **<http://www.AlanTuring.net/proposed_central_math_station>**).

292 Ibid.

293 Minutes of the Executive Committee of the National Physical Laboratory for 19 December 1944 (NPL library; a digital facsimile is in *The Turing Archive for the History of Computing* **<http://www.AlanTuring.net/npl_minutes_dec1944>**).

294 The Aiken and Stibitz machines were neither electronic nor stored-program.

295 Womersley, J. R. 'A.C.E. Project - Origin and Early History' (National Physical Laboratory, 26 November 1946), published in Copeland, B. J. *Alan Turing's Automatic Computing Engine* (Oxford and New York: Oxford University Press, 2005), pp. 38-39; a digital facsimile is in *The Turing Archive for the History of Computing* **<http://www.AlanTuring.net/ace_early_history>**).

296 Minutes of the Executive Committee of the National Physical Laboratory for 23 October 1945 (NPL library; a digital facsimile is in *The Turing Archive for the History of Computing* **<http://www.AlanTuring.net/npl_minutes_oct1945>**).

297 Woodger, M. handwritten note, no date (in the Woodger Papers, catalogue reference M15/78); letter from Woodger to Copeland (27 November 1999). Woodger records the existence of an NPL file giving the date of Turing's completed report as 1945; the file was destroyed in 1952.

298 Edward Travis was head of the British government's codebreaking operations from 1942.

299 Womersley, J. R. '"ACE" Machine Project', National Physical Laboratory, no date (Woodger Papers; a digital facsimile is in *The Turing Archive for the History of Computing* **<http://www.AlanTuring.net/womersley_ace_machine>**).

300 Womersley, J. R. ' "ACE" Machine Project', National Physical Laboratory, paper E.881, 13 February 1946 (Woodger Papers; a digital facsimile is in *The Turing Archive for the History of Computing* **<http://www.AlanTuring.net/ace_machine_project>**).

301 Minutes of the Executive Committee of the National Physical Laboratory for 19 March 1946 (NPL library; a digital facsimile is in *The Turing Archive for the History of Computing* **<http://www.AlanTuring.net/npl_minutes_mar1946>**).

302 Ibid.

303 Darwin, C. 'Automatic Computing Engine (ACE)', National Physical Laboratory, 17 April 1946 (National Archives/Public Record Office (document reference DSIR 10/385); a digital facsimile is in *The Turing Archive for the History of Computing* **<http://www.AlanTuring.net/darwin_ace>**).

304 Minutes of the DSIR Advisory Council, 8 May 1946 (National Archives/Public Record Office (document reference DSIR 10/275); a digital facsimile is in *The Turing Archive for the History of Computing* **<http://www.AlanTuring.net/dsir_minutes_may1946>**).

305 Minutes of the Executive Committee of the National Physical Laboratory for 21 May 1946 (NPL library; a digital facsimile is in *The Turing Archive for the History of Computing* **<http://www.AlanTuring.net/npl_minutes_may1946>**).

306 Letter from Woodger to Copeland (22 May 2003).

307 Letter from Woodger to Copeland (25 February 2003).

308 Memorandum from Turing to Darwin, 30 August 1947 (Woodger Papers, catalogue reference M11/99; a digital facsimile is in *The Turing Archive for the History of Computing* **<http://www.AlanTuring.net/turing_darwin_30aug47>**).

309 'Draft Report of the Executive Committee for the Year 1946',

National Physical Laboratory, paper E.910, section Ma. 1, anon., but probably by Womersley (NPL library; a digital facsimile is in *The Turing Archive for the History of Computing* **<http://www.AlanTuring.net/annual_report_1946>**).

310 Flowers in interview with Copeland (July 1996).

311 Letter from Radley to Womersley, 25 February 1946 (National Archives/Public Record Office, document reference DSIR 10/385; a digital facsimile is in *The Turing Archive for the History of Computing* **<http://www.AlanTuring.net/radley_womersley_25feb46>**).

312 Flowers in interview with Copeland (July 1998).

313 Letter from Darwin to Sir Edward Appleton, 13 August 1946 (National Archives/Public Record Office, document reference DSIR 10/275; a digital facsimile is in *The Turing Archive for the History of Computing* **<http://www.AlanTuring.net/darwin_appleton_13aug46>**); letter from Radley to Darwin, 1 November 1946 (National Archives/Public Record Office, document reference DSIR 10/385; a digital facsimile is in *The Turing Archive for the History of Computing* **<http://www.AlanTuring.net/radley_darwin_1nov46>**).

314 Letter from W. B. Lewis to Womersley, 14 August 1946 (Woodger Papers, catalogue reference M11).

315 Letter from Darwin to Appleton, 13 August 1946 (National Archives/Public Record Office, document reference DSIR 10/275; a digital facsimile is in *The Turing Archive for the History of Computing* **<http://www.AlanTuring.net/darwin_appleton_13aug46>**).

316 'Proposal to Transfer Responsibility for Certain Work at Telecommunications Research Establishment, Malvern, from Ministry of Supply to D.S.I.R.', National Physical Laboratory, paper E.895, 21 October 1946, anon. (NPL library).

317 Letter from Hiscocks to R. A. Smith, 30 October 1946 (National Archives/Public Record Office, document reference DSIR 10/385; a digital facsimile is in *The Turing Archive for the History of Computing* **<http://www.alanturing.net/turing_archive/archive/p/p12/P12-001.html>**).

318 Hiscocks as reported in 'Williams Cathode Ray Tube Storage: Evidence Relating to the Origin of the Invention and the Dissemination of Information on the Operation of the Storage System', anon., n.d., p. 9.

319 Letter from Darwin to Radley, 26 November 1946 (National Archives/Public Record Office, document reference DSIR 10/385; a digital facsimile is in *The Turing Archive for the History of Computing* **<http://www.AlanTuring.net/darwin_radley_26nov46>**).

320 Minutes of the Executive Committee of the National Physical Laboratory for 22 October 1946 (NPL library).

321 Ibid.

322 Minutes of the Executive Committee of the National Physical Laboratory for 19 November 1946 (NPL library; a digital facsimile is in *The Turing Archive for the History of Computing*

The Turing Archive for the History of Computing
<http://www.AlanTuring.net/npl_minutes_nov1946>).

323 Letter from Darwin to Smith, 13 November 1946 (National Archives/Public Record Office, document reference DSIR 10/385; a digital facsimile is in *The Turing Archive for the History of Computing* **<http://www.alanturing.net/turing_archive/archive/p/p15/P15-001.html>**).

324 Letter from Smith to Hiscocks, 2 December 1946 (National Archives/Public Record Office, document reference DSIR 10/385; a digital facsimile is in *The Turing Archive for the History of Computing* **<http://www.alanturing.net/turing_archive/archive/p/p18/P18-001.html>**).

325 Minutes of the Executive Committee of the National Physical Laboratory for 17 December 1946 (NPL library); letter from Hiscocks to Williams, 31 January 1946 (National Archive for the History of Computing, University of Manchester).

326 Minutes of the Executive Committee of the National Physical Laboratory for 19 November 1946 (NPL library; a digital facsimile is in *The Turing Archive for the History of Computing* **<http://www.AlanTuring.net/npl_minutes_nov1946>**).

327 Ibid. See also Wilkes, M. *Memoirs of a Computer Pioneer* (Cambridge, Mass.: MIT Press, 1985).

328 Memorandum from Turing to Womersley, undated, c. December 1946 (Woodger Papers, catalogue reference M15/77; a digital facsimile is in *The Turing Archive for the History of Computing* **<http://www.AlanTuring.net/turing_womersley>**).

329 'Draft Report of the Executive Committee for the Year 1946', National Physical Laboratory, paper E.910, section Ma. 1, anon., but probably by Womersley (NPL library; a digital facsimile is in *The Turing Archive for the History of Computing* **<http://www.AlanTuring.net/annual_report_1946>**).

330 Huskey, H. D. 'The ACE Test Assembly, the Pilot ACE, the Big ACE, and the Bendix G15', in Copeland, B. J. *Alan Turing's Automatic Computing Engine* (Oxford and New York: Oxford University Press, 2005).

331 Jack Good in interview with Copeland (28 February 2004). Whether the visit actually took place is not known, since Good was admitted to hospital for a few weeks (letter from Good to Copeland, 14 June 2007).

332 Minutes of the Executive Committee of the National Physical Laboratory for 21 January 1947 (NPL library; a digital facsimile is in *The Turing Archive for the History of Computing* **<http://www.AlanTuring.net/npl_minutes_jan1947>**).

333 Wilkinson in interview with Evans in 1976 ('The Pioneers of Computing: An Oral History of Computing' (London: Science Museum)), transcription by Copeland; memorandum from Turing to Darwin, 30 August 1947 (Woodger Papers, catalogue reference M11/99; a digital facsimile is in *The Turing Archive for the History of Computing* **<http://www.AlanTuring.net/turing_darwin_30aug47>**).

334 Woodger in interview with Copeland (June 1998); Woodger, M. 'ACE Test Assembly, Sept./Oct. 1947', National Physical Laboratory, no date (Woodger Papers, catalogue reference M15/84; a digital facsimile is in *The Turing Archive for the History of Computing* **<http://www.AlanTuring.net/test_assembly>**).

<http://www.AlanTuring.net/test_assembly>).

335 Womersley, J. R. 'A.C.E. Project', National Physical Laboratory, no date, attached to a letter from Womersley to the Secretary of the NPL dated 21 August 1947 (National Archives/Public Record Office, document reference DSIR 10/385; a digital facsimile is in *The Turing Archive for the History of Computing* **<http://www.AlanTuring.net/womersley_ace_project>**).

336 Wilkinson in interview with Evans in 1976 ('The Pioneers of Computing: An Oral History of Computing' (London: Science Museum)), transcription by Copeland.

337 Woodger in interview with Copeland (June 1998).

338 Letter from Huskey to Copeland (3 June 2003).

339 Wilkinson in interview with Evans in 1976 ('The Pioneers of Computing: An Oral History of Computing' (London: Science Museum)), transcription by Copeland.

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