Alan Turing's Automatic Computing Engine

The Master Codebreaker's Struggle to Build the Modern Computer

Edited by
B. Jack Copeland

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Contents

Part V Technical Reports and Lectures on the ACE 1945–47

List of Photographs

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David Clayden joined the National Physical Laboratory (NPL) in 1947 and was a designer of the Pilot Model ACE and of the Big ACE. He subsequently worked on optical character recognition, the RSA encryption algorithm, and various other projects. He retired from the NPL in 1981.

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Donald Davies FRS heard of the planned Automatic Computing Engine while in his final year at university and immediately applied to join the NPL, becoming in 1947 a member of the small team surrounding Turing. Davies was a designer of the Pilot Model ACE and of the Big ACE. From 1966 he headed the NPL's Autonomics Division. Davies invented 'packet switching', used in the ARPANET (forerunner of the Internet), and from 1979 worked on data security and public key cryptosystems. His books include, with D. Barber, *Communication Networks for Computers* (Chichester: Wiley, 1973) and, with W. Price, *Security for Computer Networks* (Chichester: Wiley, 1984). He died in 2000.

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Harry Huskey was teaching mathematics at the University of Pennsylvania when by chance he applied for part-time work on the ENIAC. Thereafter he was an important figure in a number of the early computer projects, including the EDVAC, the ACE, and the SEAC. He designed the SWAC (Standards Western Automatic Computer) and the Bendix G15 computer. Huskey is Professor Emeritus at the University of California.

Eileen Magnello is Research Associate at the Wellcome Trust Centre for the History of Medicine at University College, London. Her publications include *An Illustrated History of the National Physical Laboratory: A Century of Measurement* (Bath: Canopus, 2000).

Henry John Norton joined Turing's group at the NPL in 1947 and was involved in programming the Pilot Model ACE. He now teaches computer architecture at King's College, London.

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Diane Proudfoot is Senior Lecturer in Philosophy at the University of Canterbury, New Zealand and Co-Director of The Turing Archive for the History of Computing. She is the author of a number of academic and popular articles on Turing's work.

Alan Turing FRS invented the 'universal computing machine', on which all electronic stored-program digital computers are based, in 1936. Following his crucial wartime work breaking German codes, Turing joined the NPL in 1945 to design the Automatic Computing Engine. He left in 1948 to take up a Readership at the University of Manchester. Turing pioneered Artificial Intelligence and Artificial Life. He died in 1954.

Tom Vickers joined the NPL in 1946 after wartime work in armaments research. Once the Pilot Model ACE was operational, Vickers became the manager of the computing service based around it—the first external scientific computing service in the world. He subsequently became Head of the NPL's General Computing Group. After retiring from the NPL in 1977, he worked as a member of the Computing Board of the Council for National Academic Awards, taking a wide interest in computer education.

Robin Vowels was from 1961 to 1964 engineer-in-charge and programmer of an English Electric DEUCE at the New South Wales University of Technology. Vowels was thereafter Senior Lecturer in Computer Science at the Royal Melbourne Institute of Technology, retiring in 1998. He is the author of several textbooks on computer programming.

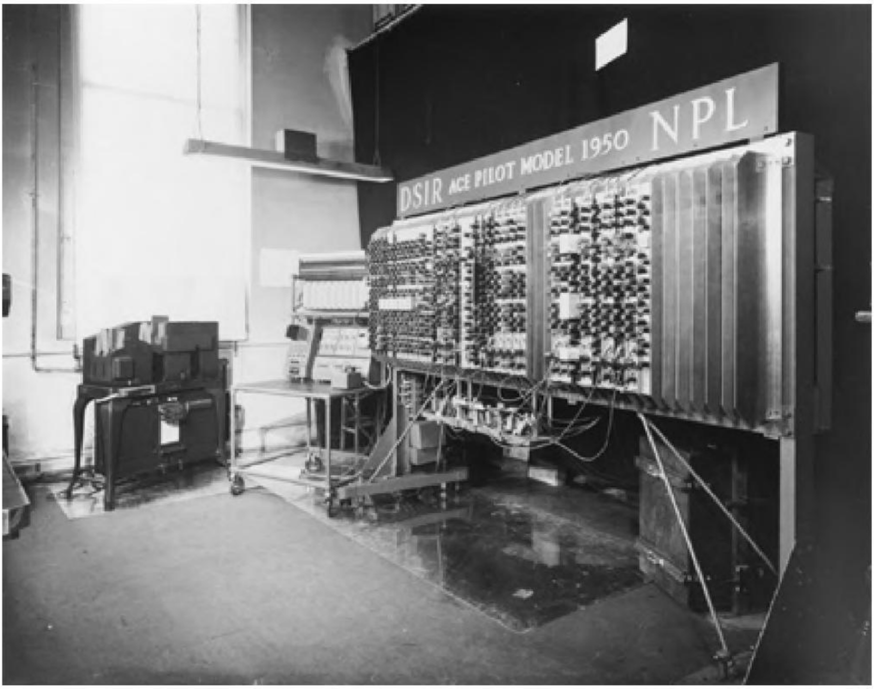
Benjamin Wells is Professor of Mathematics and Computer Science at the University of San Francisco. The last doctoral student of noted mathematical logician Alfred Tarski, Wells works in the intersection of logic, algebra, and computing. He also works in the areas of computer graphics and visual communication.

Maurice Wilkes FRS designed and built the University of Cambridge EDSAC. The EDSAC, which first ran in 1949, was the second electronic stored-program computer to work. Wilkes was Professor of Computer Technology at Cambridge and Director of the Computer Laboratory there until 1980, when he became an Adjunct Professor at MIT and a Senior Consulting Engineer at Digital Equipment Corporation, later working with Olivetti Research. He was knighted in 2000. His books include *Memoirs of a Computer Pioneer* (Cambridge, Mass: MIT Press, 1985).

Jim Wilkinson FRS joined the NPL in 1946 after wartime work in armaments research. Wilkinson worked first as Turing's assistant and then, after Turing left the NPL, headed the ACE Section. Wilkinson contributed to the design of the ACE Test Assembly and played a key role in the design and construction of the Pilot Model ACE; he also contributed to the design of the Big ACE. Once the Pilot Model ACE was operational, Wilkinson concentrated on the development of numerical analysis. He is the author of several standard works in the field. In 1970 he received the A. M. Turing Award of the Association for Computing Machinery for his unique contributions to computational mathematics. Wilkinson retired from the NPL in 1980. He died in 1986.

Mike Woodger joined Turing and Wilkinson at the NPL in 1946. He contributed to the design of the ACE Test Assembly, the Pilot Model ACE, and the Big ACE. Woodger is co-author of Algol 60, the first international programming language. He also played a part in developing the real-time programming language Ada, co-editing the 1980 Reference Manual for the language and the 1983 ANSI standard. He retired from the NPL in 1983.

Alan M. Turing



The Pilot Model of the Automatic Computing Engine

Introduction

B. Jack Copeland

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 (1943) 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. His 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.[1] 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 that, by making use of coded instructions stored in memory, could change itself, chameleonlike, 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. Turing saw that speed and memory were the keys to computing (in the words of his assistant, Jim Wilkinson, Turing 'was obsessed with the idea of speed on the machine'[2]). 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 (enormous by the standards of his day).

In the United States the Hungarian American mathematician John von Neumann shared Turing's dream of building an electronic 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 1936–8, 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's ACE and the EDVAC differed fundamentally in design. The ACE was a 'low level' machine (a point taken up in the chapter 'Computer Architecture and the ACE Computers')—programs were made up entirely of instructions like 'Transfer the contents of

Temporary Store 15 to Temporary Store 16'. 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 associated with them. For example, if two numbers were transferred to a certain destination in memory their sum would be formed there, ready to be transferred elsewhere by a subsequent instruction. Instead of writing mathematically significant instructions such as

Multiply *x* by *y* and store the result in *z*, the programmer composed a series of low-level transfer instructions producing that effect. A related difference was that, in Turing's design, complex behaviour was to be achieved by complex programming rather than by complex equipment: his 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'.[4]

In order to increase the speed of a program's execution, Turing proposed that instructions be stored, not consecutively, but at carefully chosen positions in memory, with each instruction containing a reference to the position of the next. Also with a view to speed, he included a small fast-access memory for the temporary storage of whichever numbers were used most frequently 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.'[5]

The delays mentioned by Davies in the Foreword (and described more fully in the chapter 'The Origins and Development of the ACE Project') meant that it was several years after the completion of '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 sophisticated mathematical programs for the planned machine. The result of these delays, which were not of Turing's making, was that 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 'greeted with hilarity' by Turing's group.[6]

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. Newman, like von Neumann in the United States, was profoundly influenced by Turing's pre-war conception of a universal computing machine. Frustrated by the delays at the NPL, and eager to get his hands at last on a stored-program computer, Turing accepted his friend's offer of a job and left London for Manchester.

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 Pilot ACE was preceded by several other electronic stored-program computers. The EDSAC, built by Maurice Wilkes at the University of Cambridge Mathematical Laboratory, was the second to run, in May 1949. Later in 1949 came the BINAC, built by the creators of the ENIAC, Presper Eckert and John Mauchly, at their Electronic Control Company, Philadelphia (opinions differ as to whether the BINAC ever actually worked, however), 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 US Bureau of Standards Eastern Division, Washington DC, first ran in April 1950. The EDVAC itself was not completed until 1952 but most of the computers just mentioned were influenced by the EDVAC 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'.[7] The last DEUCE went out of service in about 1970.

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 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 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.[8] Over 400 were sold worldwide and the G15 remained in use until about 1970.

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 EMI 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, the low-cost transistorized Packard-Bell PB250, and the 'Big ACE', constructed at the NPL and fully operational in 1960.[9]

This book tells the story of the ACE computers. Much of it is in the words of the pioneers who designed or programmed these machines: Clayden, Davies, Hayes, Huskey, Norton, Vowels, Vickers, Wilkinson, Woodger, and, of course, Alan Turing himself. Wilkes compares the electronic techniques that he used in the EDSAC with those adopted in the Pilot ACE. Chapters by Magnello, Croarken, and Copeland explain how Britain's first attempt to build an electronic stored-program computer came to take place at the NPL and describe the ups and downs of the ACE project. Chapters by Copeland and Proudfoot, Campbell-Kelly, Numerico, and Doran assess the ACE computers, evaluate their impact, and investigate the claim—based upon the influence of his pre-war work—that Turing is the father of the modern computer. Turing's work on Artificial Intelligence and Artificial Life is also described.[10]

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 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.

'ACE' WILL SPEED JET FLYING

SOLVING PROBLEMS IN AERODYNAMICS

DAILY TELEGRAPH REPORTER

Revolutionary developments in aerodynamics, which will enable jet-planes to fly at speeds vastly in excess of that of sound, are expected to follow the British invention of "Ace," which has been commonly labelled the electronic "brain."

The machine, as reported in THE DAILY TELEGRAPH yesterday, will solve in seconds abstruse mathematical problems which baffle the human brain for weeks. It will be able to determine the momentum of the airflow around aircraft at speeds greater than that of sound, which experts in aerodynamics would otherwise have little hope of obtaining.

At the National Physical Laboratory at Teddington yesterday the three scientists chiefly responsible for Ace — automatic computing machine—told me about their invention.

They are Dr. A. M. TURING, Dr. J. R. WOMERSLEY, superintendent of the mathematics division of the laboratory, and Prof. D. HARTREE, who worked on Eniac, the American equivalent of Ace.

1,000 TIMES FASTER

Prof. Hartree said: "The implications of the machine are so vast that even we cannot conceive how they will affect our civilisation. Here you have something which is making one field of human activity 1,000 times faster.

In the field of transport, the equivalent of Ace would be the ability to travel from London to Cambridge—about 52 miles—in five seconds as a regular thing. It is almost unimaginable."

Prof. Hartree disclosed for the first time that a third electronic computer—at the Institute for Advanced Studies at Princeton, New Jersey—was in the course of preparation.

Although mathematical plans were almost complete, he said, it was not likely that Ace would be in full operation for two years. Experiments on parts of the machine would, however, be carried on in the meantime.

LIKE TELEPHONE EXCHANGE

New facts given to me about the machine were:

It will use about 5,000 radio valves, as compared with the 18,000 required by Eniac.

Like Eniac, it will resemble the racks in a telephone exchange.

It will do 150,000,000 multiplications of 10 digit numbers in a week and write the results. One man engaged merely in copying down the results would take, Prof. Hartree estimated, 500 years.

Dr. Turing, who conceived the idea of Ace, said that he foresaw the time, possibly in 30 years, when it would be as easy to ask the machine a question as to ask a man.

Dr. Hartree, however, thought that the machine would always require a great deal of thought on the part of the operator.

He deprecated, he said, any notion that Ace could ever be a complete substitute for the human brain, adding:

"The fashion which has sprung up in the last 20 years to decry human reason is a path which leads straight to Nazism."

The Daily Telegraph, 8 November 1946.

Source: By permission of Telegraph Group Ltd.

"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.

Source: By permission of Telegraph Group Ltd.

MONTH'S WORK IN A MINUTE

ACE CALCULATOR

FROM OUR SPECIAL CORRESPONDENT

TEDDINGTON, Nov. 29

With the completion of the pilot model of the National Physical Laboratory's automatic computing engine, known as Ace, the Department of Scientific and Industrial Research will be glad to hear of problems the solving of which requires long and intricate arithmetical calculations. The Ace itself will be built later, but the model demonstrated here to-day is none the less a complete electronic calculating machine, claimed as one of the fastest and most powerful computing devices in the world.

Its function is to satisfy the ever-increasing need in science, industry, and administration, for rapid mathematical calculation which in the past, by traditional methods, would have been physically impossible or required more time than the problems justified. The speed at which this new engine works, said Dr. E. C. Bullard, F.R.S., director of the laboratory, could perhaps be grasped from the fact that it could provide the correct answer in one minute to a problem that would occupy a mathematician for a month. In a quarter of an hour it can produce a calculation that by hand (if it were possible) would fill half a million sheets of foolscap paper.

The automatic computing engine uses pulses of electricity, generated at a rate of a million a second, to solve all calculations which resolve themselves into addition, subtraction, multiplication, and division; so that for practical purposes there is no limit to what Ace can do.

HOLED CARDS

On the machine the pulses are used to indicate the figure 1, while gaps represent the figure 0. All calculations are done with only these two digits in what is known as the binary scale. When a sum is put into the machine the numbers are first translated into the binary scale and coded; instructions are also given to the machine by coding them as holes in cards. To carry out long sequences of operations the engine must be endowed with a "memory."

This "memory" section is highly complicated. It depends upon the slower time of travel of supersonic waves, into which the electric pulses are converted, through a column of mercury. One thousand pulses—representing digits—can be stored in this way and extracted at the precise moment when they are needed by the "arithmetic section," which handling pulses of electricity, is working 100,000 times faster than the supersonic section. The completed calculation appears in code as a holed card, representing the answer in the binary scale, which is translated back into ordinary numbers.

When experience has been gained some improvements will doubtless be made to the pilot Ace and embodied in the first standard prototype model. The cost of development and construction of the pilot model, which uses some 800 thermionic valves, was about £40,000. Now it is ready to "do business" and is expected to more than earn its keep.

The Times, 30 November 1950.

Source: By permission of Times Newspapers Ltd.

The DEUCE, the production model of the Pilot ACE, manufactured by the English Electric Company. This DEUCE, photographed in 1956, was installed at the National Physical Laboratory in 1955.
Source: National Physical Laboratory. © Crown copyright; reproduced by permission of the Controller of HMSO.

Notes

1. Turing, A. M. (1936) 'On computable numbers, with an application to the Entscheidungsproblem', *Proceedings of the London Mathematical Society*, Series 2, 42 (1936–37), 230–65.
2. Wilkinson in interview with Christopher Evans in 1976 (*The Pioneers of Computing: An Oral History of Computing*. London: Science Museum).
3. Letter from Huskey to Copeland (4 February 2002).
4. 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 <www.AlanTuring.net/turing_womersley_cdec46>).

5. Letter from Wilkinson to Newman, 10 June 1955 (among the Turing Papers in the Modern Archive Centre, King's College, Cambridge (catalogue reference A.7)).
6. Woodger in interview with Copeland (June 1998).
7. Sir Charles Darwin, 'Automatic Computing Engine (ACE)', 17 April 1946 (in the British Public Record Office (PRO), Kew, Richmond, Surrey (document reference DSIR 10/385); a digital facsimile is in The Turing Archive for the History of Computing <www.AlanTuring.net/darwin_ace>). A leading British expert on automatic computation, Douglas Hartree, appears to have thought that on the contrary a total of three digital computers would probably be adequate for the country's computing needs (Hartree's opinion is reported by Vivian Bowden (1975) in 'The 25th anniversary of the stored program computer', *The Radio and Electronic Engineer*, 45, 326.
8. Letter from Huskey to Copeland (20 December 2001).
9. Coombs, A. W. M. (1954) 'MOSAIC', in *Automatic Digital Computation: Proceedings of a Symposium Held at the National Physical Laboratory*. London: Her Majesty's Stationery Office; Froggatt, R. J. (1957) 'Logical design of a computer for business use', *Journal of the British Institution of Radio Engineers*, 17, 681–96; Bell, C. G. and Newell, A. (1971) *Computer Structures: Readings and Examples.* New York: McGraw-Hill, pp. 44, 74; Yates, D. M. (1997) *Turing's Legacy: A History of Computing at the National Physical Laboratory 1945–1995*. London: Science Museum.
10. This book grew out of the ACE 2000 Conference, a joint meeting of the British Society for the History of Science and the Computer Conservation Society, organized by Copeland in order to mark the 50th Anniversary of the Pilot Model ACE. ACE 2000 was held on 18–19 May 2000 at the London Science Museum and the National Physical Laboratory. A total of 103 people attended and 18 papers were presented. Details of the conference, including the programme and a list of the attendees, is at <www.AlanTuring.net/

ace2000>. Thirteen chapters of this volume are derived from papers presented at ACE 2000.

Part I
The National Physical Laboratory and the ACE Project

1 *The National Physical Laboratory*

Eileen Magnello

The campaign for the endowment of science

The National Physical Laboratory (NPL), one of the world's great national standards laboratories, has its origins in the campaign for the endowment of science in the latter part of the nineteenth century. The first serious debate about the role of science in British industry took place in response to the Paris International Exhibition of 1867, at which continental manufacturers won a significantly larger proportion of the prizes than at previous exhibitions. Although the finest examples of British industry (such as the 1866 Atlantic telegraph cable) were not represented, many agreed on the basis of the Paris Exhibition that unless scientific education was increased, Britain was bound eventually to be eclipsed by competitor nations.[1] In response to this threat the Liberal Government of 1870 enacted a scheme of universal primary education, in order to promote a minimum standard of literacy and numeracy in the workforce. More tellingly, industrial communities across the country (notably in Leeds, Birmingham, and Sheffield) sponsored the creation of their own new civic colleges, later universities, with little support from the government. These soon developed their own facilities for laboratory research.

The campaign for the endowment of science found a strong ally in the journal *Nature*, established in 1869. Even in its early issues it lobbied for an enquiry into the state of science in Britain. The journal's editor, Norman Lockyer, drew attention to the involvement of the German government in promoting science, noting that Britain had resources and talent of the same order as Germany, but lacked government help.[2]

In February 1870 the Liberal prime minister, William Gladstone, agreed to appoint a Royal Commission under William Cavendish, the seventh Duke of Devonshire, to study the existing national provision for scientific instruction and for the advancement of science. Lockyer's persistence, and the testimony of sympathetic witnesses from the scientific community, succeeded in persuading the Devonshire Commission that government aid, especially in the form of funds for the establishment of public laboratories, was essential to the future of science. In 1874 the Commission recommended that a national technical laboratory and physical observatory be built.[3]

A national standards laboratory

Although *Nature* conceded that the recent establishment of the Davy–Faraday Laboratory at the Royal Institution met some existing industrial needs, it argued that much more was required. In his presidential address to the British Association in 1895, Sir Douglas Galton uttered a plea for the foundation of a national physical laboratory supported by government funding. He proposed that the new laboratory be managed by the Royal Society, with a substantial sum of money allotted by the government for an extension to the Kew Observatory, along the lines of the *Reichsanstalt* in Berlin (the German state repository for determining standards).[4] The Kew Observatory had long been the national centre for calibrating magnetic and meteorological instruments.

It was resolved that a public institution should be established to determine and verify instruments, test materials, determine physical constants, and undertake investigations into the strength and durability of materials. The first NPL Executive Committee meeting was held on 16 May 1899, with Lord Rayleigh (brother-in-law of Arthur Balfour, First Lord of the Treasury) in the Chair. Members of the General Board of the NPL were named. At a second meeting on 5 July it was recommended that Richard Tetley Glazebrook be appointed director of the Laboratory, from 1 January 1900.[5] Glazebrook had established his reputation as a manager while Senior Bursar of Trinity College, Cambridge (a position he held from 1895).[6]

Finding a site for the NPL

The Executive Committee still had to determine the most suitable location for building the Laboratory. They visited sites at Eltham in Kent, Oxshott in Surrey, and Hainault Forest in Essex, all of which were deemed unsatisfactory. Hints reached Glazebrook that Bushy House in Teddington, near London, might be offered as an alternative to Kew.[7] He and his Executive Committee decided that Bushy House suited their requirements. The Laboratory was established in the existing building and opportunities for work opened in many directions (including the standards and verification work previously carried out at the Kew Observatory).

Bushy House today. The Pilot Model of the Automatic Computing Engine was built here in what was originally the butler's pantry.

In May 1901 the Finance Committee of the NPL recommended that, in order to help create a feeling of institutional camaraderie, Glazebrook and his family take the second floor of the north wing of Bushy House as a private residence. Glazebrook's residence had a wine cellar, a coal cellar, a bicycle shed, and a small enclosed yard—accommodation not unlike that of an Oxbridge college, and Glazebrook had similar status to the head of a college.[8]

The work of the NPL to 1918

In 1901 work began on converting the ground floor and basement of Bushy House into a physics laboratory. Other parts of the building were arranged as temporary laboratories for electrical, magnetic, and thermometric work, in addition to metallurgical and chemical research, all of which were considered to be the most fundamental areas, and had to be accommodated first. By April the contract for an engineering building had been settled and construction had begun. In the early part of 1905 plans were made to erect an electrotechnics building and a building for metrology.[9]

By 1908 the Executive Committee had extended its research programmes to include the study of problems of travel by air and sea. A tank was installed to enable shipping research to be carried out and plans were drawn up for a pioneering programme of aeronautical research. A division was set up to deal with the testing of road materials. With the approach of war, a programme was put in place for research into the production of optical glass—required urgently for telescopes, binoculars, range-finders, prismatic compasses, and periscopes.[10]

In 1915 the Executive Committee of the NPL considered for the first time the idea of employing women. Some members of the Committee thought that this would lead to objections from among the gauge-makers, and the scheme was dropped. Just a few months later, however, increasing demands from the Munitions Department resulted in the enlistment of women. On the insistence of Glazebrook and the Executive Committee, the women who joined the NPL were paid at the same rates as men.

The interwar period

In 1916 Lord Haldane had announced the government's intention of forming a Department of Scientific and Industrial Research (DSIR).[11] Heated debate followed over whether the Royal Society or the new department should control the NPL. Glazebrook wanted the President and Council of the Royal Society to have scientific control of the NPL, and at first the DSIR was out manoeuvred by the Royal Society.[12] However, with Glazebrook's retirement in 1919 and the impact on the NPL of the unsatisfactory economic climate of the 1920s, the Royal Society lost effective control of the Laboratory.

The interwar period saw a decline of the older established industries like heavy engineering and shipbuilding, and the growth of new science-based industries such as radio, electrical power generation and transmission, non-ferrous metallurgy, synthetic polymers, aeronautics, motor engineering, and motion pictures. Industry became more responsive to the need for scientific expertise. In 1919 the engineer and physicist Sir Joseph Petavel was appointed director of the NPL. Previously Petavel had worked at the Davy–Faraday Laboratory at the Royal Institution, where he had established the primary standard of light and had designed an indicator for measuring pressures set up in exploding gaseous mixtures (later known as the 'Petavel Gauge').[13] With his background in engineering, Petavel tended to value short-term research for direct industrial gain more than longer-term speculative research. This attitude found favour with the DSIR. Under Petavel the Laboratory became oriented toward the pursuit of scientific innovation for industrial application.

The Laboratory also became involved in practical projects affecting the daily lives of the public. Illumination problems were regarded as being of great national importance, since they affected the health and safety of the public in relation to the lighting of homes and other buildings, vehicles, streets, and open spaces. In 1924 the DSIR directed the NPL to undertake illumination research for the entire nation. A Sound Division was added to the Laboratory in 1922, carrying out work on the acoustics of buildings and studying sound transmission problems in connection with the telephone, the gramophone, and radio broadcasting. Other research of the Laboratory included investigation into the wind forces on roofs and structures, the vibrations of buildings, the expansion of concrete, and the acoustical problems of the Royal Albert Hall.

Relations between the NPL and the DSIR deteriorated as Britain entered the depression. The Treasury reduced expenditure in all government departments and basic innovative research received little attention from the government. A rapid change of directors at the NPL during the 1930s did not help its position, preventing the implementation of any plans for long-term development. Following Petavel's death in 1936, Sir Frank Edward Smith (employed at the NPL since 1900) became its acting director. In 1937 Smith was replaced by Sir William Lawrence Bragg, who left after only ten months to take up the Chair of Experimental Physics at the Cavendish Laboratory in Cambridge.

Bragg was succeeded by Sir Charles Darwin, grandson of the famous evolutionary biologist. Darwin remained director until 1949. His administrative talents were demonstrated by his reorganization of the Laboratory both before and after the Second World War. Darwin played a leading role in the decision to involve the NPL in the construction of an electronic digital computer, the Automatic Computing Engine.

The Second World War

By 1941 all departments of the Laboratory were providing assistance to the Armed Services and most of its staff were involved full time in the war effort. Darwin was seconded to the position of director of the Central Scientific Office British Supply Council in Washington DC, his brief to improve Anglo-American scientific cooperation. He stayed in Washington for six months. Edward Appleton, Secretary of the DSIR, acted as director of the NPL during Darwin's absence. When Darwin returned to Britain he was made scientific advisor to the Army Council, in addition to continuing as director at the NPL. He resumed his full-time duties at the Laboratory in 1943.

During the early 1930s a Radio Research Station had been established by the DSIR and a Wireless (later Radio) Division was created at the NPL to cooperate in this work. By 1933 radio direction finding, later known as ‘radar’, was being pursued. It was claimed at the end of the war that radar (which offered a method of detecting the position of aircraft by bouncing radio waves off them) was the most important national asset to have emerged from the NPL.[14] Other important war work undertaken at the NPL included the organization of the British research on the atomic bomb, and research in ‘electronics’—a term that was used to include investigations into the principles and design of electronic valve circuits and also the study of their very wide applications.

Because of the increasing emphasis on industrial quality control, brought about largely by the demands of the war, industry was growing more receptive to the adoption of various statistical tools. It became evident to Darwin that there was a need to establish a centre for statistical and other mathematical research. The result, with the arrival of peace in 1945, was the creation at the NPL of a Mathematics Division (Chapter 2).

In 1945 both mathematics and electronics stood on the brink of a new, digital, future. Alan Turing, who joined the newly formed Mathematics Division in October of that year, could see this future clearly.

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2 *The creation of the NPL Mathematics Division*

Mary Croarken

Introduction

In April 1945 the journal *Nature* announced that the National Physical Laboratory was to 'extend its activities by the establishment of a Mathematics Division'.[1] This announcement coincided with John Womersley's official appointment to the post of superintendent of the Division and saw the beginning of computer research at the NPL. The new Mathematics Division was intended to act as a 'central mathematics station' and was the first of the three main centres of early electronic computer development in Britain. The Division had two main functions: to undertake research into new computing methods and machines, and to provide computing services and advice to government departments and to industry. It was soon providing a national computing service, and became a leading centre for numerical analysis.

This chapter sets the stage for these developments in computing, focusing on the circumstances surrounding the creation of the NPL Mathematics Division. Four questions are discussed. Why was a central mathematics station needed? Why was it established at the NPL? Why was Womersley chosen as superintendent? And finally, to what extent did the NPL Mathematics Division succeed as a central mathematics station?

A Central Mathematics Station

The Second World War had a huge effect on how computation—i.e. calculation—was perceived and undertaken. The war increased the demand for scientific and statistical computation (in terms both of bulk and complexity). The increase was most pronounced in two areas:

ballistics, and applied research into new forms of weapons and defence. Several specialist calculating groups were set up around the country in response to the increasing demand for computation.

The newly created Ministry of Supply was particularly active in promoting such groups, since it supported a great deal of applied research. Just before war was declared, the Ministry of Supply's External Ballistics Department took over the newly created Cambridge Mathematical Laboratory.[2] The Cambridge Laboratory had been created by John Lennard-Jones as a central computing resource for Cambridge scientists. (Lennard-Jones was Plummer Professor of Theoretical Chemistry at Cambridge and worked for the Ministry of Supply during the war, holding the positions of chief superintendent of Armament Research and, in 1945, director general of Scientific Research in the Ministry of Supply.) The Cambridge Mathematical Laboratory housed a type of mechanical analogue computing machine called a differential analyser, and was also equipped with desk calculating machines (see the photograph on the following page), a model differential analyser, and a machine for solving simultaneous equations (known as the 'Mallock machine' after its inventor). Lennard-Jones recruited several mathematicians to work for the External Ballistics Department, including E. T. (Charles) Goodwin, James Wilkinson, and Tom Vickers, all of whom were later closely associated with the Automatic Computing Engine (ACE). During the war some of the staff were transferred to computational work at the Armaments Research Department at Fort Halstead, and others moved into the Admiralty.

In addition the Ministry of Supply took over Professor Douglas Hartree's differential analyser at the University of Manchester and also had a group working on internal ballistics problems at Woolwich, where Womersley was employed. In July 1942, the Ministry of Supply created a statistical service called S. R. 17 headed by Womersley.

The Ministry of Aircraft Production used R. V. Southwell's group at the University of Oxford to help with stress calculations for aircraft structures. One of Southwell's young students was Leslie Fox. The Royal Aircraft Establishment at Farnborough was also trying to cope with overwhelming computational difficulties and had a computing section whose staff included T. B. Boss. Boss and Fox were both to join the NPL Mathematics Division.

The War Office, the Air Ministry, and the Ministry of Supply contracted out some of their calculating work to the Scientific Computing Service Ltd. This was a commercial computing bureau set up in 1937 by L. J. Comrie, ex-superintendent of the Nautical Almanac Office, and Britain's leading mathematical table maker.[3] Comrie and his staff were in very great demand during the war, working throughout the Blitz to provide calculations for the service ministries. The type of work that they performed varied from producing ballistics tables to calculations for locating German radio transmitters.[4]

Types of desk calculating machine. Before the advent of electronic computers such as the Pilot ACE, many large-scale calculations were done by teams of clerks—known as 'human computers'—equipped with desk machines.

Source: National Physical Laboratory. © Crown copyright; reproduced by permission of the Controller of HMSO.

The Ministry that took the most decisive steps to resolve its computational problems was the Admiralty. The Admiralty already had an extensive computing facility in the form of the Nautical Almanac Office, which produced astronomical and navigational tables on an annual basis. By the standards of the day it was very well equipped with desk calculators and accounting machines, and it had a well-trained staff. During the 1930s the then superintendent, Comrie, had carried out work for the War Office using Nautical Almanac Office facilities and had been dismissed for doing so.[5] It was ironic that it was the Nautical Almanac Office to which the Admiralty and others turned for computational help during the war. By January 1942, 30 per cent of the Nautical Almanac Office's work was specifically warrelated. The Office was under-resourced for the amount of work it was being asked to take on, and as early as 1941 the superintendent, Donald Sadler, suggested to the Hydrographer of the Navy that a National Computing Service be set up.[6] Sadler's suggestion came to nothing at the time, however.

The less ambitious idea to create an Admiralty Computing Service came from elsewhere. John Todd was on the staff of the director of Scientific Research Admiralty. Todd's previous postings had involved him in calculations concerning the design of mines and had convinced him that computations within applied departments were being carried out by inexperienced workers who regarded calculation as a chore.[7] He concluded that it would be both more effective and more efficient to centralize computing efforts within the Admiralty. Todd's superior, J. A. Carroll (an astronomer in peacetime), suggested that the Nautical Almanac Office would be a good place to carry out the actual computations involved. In late 1942 Sadler was asked to report on the suggestion that an Admiralty Computing Service be created. He endorsed the idea and by March 1943 the Admiralty Computing Service had been set up, its brief to advise on and to carry out computational tasks for Admiralty establishments.

The Service was administered in London by Todd and a small mathematical staff, and the computations that were required were carried out at the Nautical Almanac Office (evacuated to Bath by that time). Sadler began to recruit staff for the Service, which at its peak employed some 15–20 people. Those recruited included Goodwin, Fox, and Frank Olver. In addition the Admiralty Computing Service used a variety of mathematical consultants to help guide their work. This is not the place to give a full account of the work of the Service, but of its usefulness there is no doubt.[8] It carried out two kinds of work: large, repetitive calculations and complex mathematics. Its success was one of the main factors in the creation of the NPL Mathematics Division.

Todd and Sadler realized the limitations of the Admiralty Computing Service within a year of its getting started. It did not operate on a large enough scale to run a fully equipped computing service, and was too small to justify the purchase of punched-card tabulating machines, a differential analyser, or a more diverse selection of hand calculating machines. Consequently Todd, Sadler, and Arthur Érdelyi (a mathematical consultant who worked for the Admiralty Computing Service) wrote their *Memorandum on the Centralization of Computation in a National Mathematical Laboratory*[9] and sent it to Sir Edward Appleton, Secretary of the Department of Scientific and Industrial Research (DSIR). In it they presented a case for a National Mathematical Laboratory (emphasizing operating efficiency and economies of scale). They also recognized that the Admiralty Computing Service's role as a computing bureau could be extended to include research, and pointed out that the development of new computing methods and machines would be a valuable additional function of the National Laboratory.

For a number of reasons Appleton and the DSIR took the proposal to create a National Laboratory seriously. First, the proposals were based on the practical experience of running the Admiralty Computing Service. Second, the extensive use that the armed services were making of Comrie's Scientific Computing Service proved that government scientists needed extra computing resources. (Appleton himself had made use of Comrie's Service for calculations concerning the height variations in the E-layer of the ionosphere.) Third, a similar suggestion had been voiced in other influential quarters.

That voice belonged to Sir Charles Galton Darwin, director of the NPL. In March 1943 Darwin had remarked to a meeting of the DSIR Advisory Council that 'He was inclining more and more to the opinion that a Mathematical Department should be established at the National Physical Laboratory'.[10] Appleton had been at that meeting. Darwin followed up these remarks in a paper to the NPL Executive Committee sometime in mid- to late-1943.[11] He identified a need for a statistical department at the NPL, aimed especially at quality control problems for mass production in industry. Darwin also commented, in a small paragraph tucked away in the middle of the paper, 'that there may well be scope in making new inventions of mathematical machines'.

Earlier in the war Darwin had spent a year in Washington as director of a project to improve liaison between Britain and the United States over the scientific war effort (in what later became known as the British Central Scientific Office). Darwin was privy to the work of the MAUD committee on the atomic bomb and would probably have heard about calculating machine projects such as Howard Aiken's Sequence Controlled Calculator at Harvard University (see Chapter 3). He may also have been familiar with the computational work being done with differential analysers at the Moore School of Electrical Engineering, part of the University of Pennsylvania. (Later, in the spring of 1943, the influential ENIAC project started at the Moore School.) Perhaps Darwin's suggestion that computing machine research be carried out at the NPL was to some extent based on his knowledge of American developments.

Darwin sounded out other senior scientific figures. Darwin, Lennard-Jones (originator of the Cambridge Mathematical Laboratory), and R. H. Fowler (Plummer Professor of Mathematical Physics at Cambridge and a member of the NPL Executive Committee) discussed the possibility of a National Mathematical Laboratory over lunch on 27 May 1943. From Lennard-Jones's notes of the meeting[12] it is clear that Hartree too had been consulted. Hartree, a leading expert on calculating machines (and soon to become a member of the NPL Executive Committee), was privy to information about the US wartime calculating machine projects.

Overall, then, the time was ripe for the creation of a National Mathematical Laboratory. The DSIR set up an Interdepartmental Technical Committee to report on the issue and to work out the details.

The DSIR Interdepartmental Technical Committee

The Committee consisted of 20 members, drawn from 11 different government departments (see Table 1). Familiar faces included Darwin as chairman, Sadler, Todd, Hartree, and Womersley.

Many members of the Committee had practical computing or statistical experience. The Committee's report reflected a realization that computing machinery research needed to be sponsored by the government—a year ahead of von Neumann's 1945 draft report on the EDVAC.

The Committee reported to the DSIR Advisory Council on 10 May 1944,[13] recommending that a Central Mathematical Station be established which would:

1. Undertake research into new computing methods and machines.
2. Encourage the development of new computing methods and machines by the dissemination of knowledge.
3. Deal with statistical problems arising from industry, the physical sciences and engineering.
4. Advise on and, if necessary, prepare mathematical tables.
5. Provide computing services for government departments, industry, and universities.
6. Act as a consultant on mathematical and statistical techniques.

Table 1 The DSIR Interdepartmental Technical Committee membership[a]

Member	Representing
Sir Harold Spencer-Jones	Admiralty
Prof. J. A. Carroll	Admiralty
Mr D. H. Sadler	Admiralty
Mr J. Todd	Admiralty
Dr F. Yates	Agricultural Research Council
Prof. W. J. Duncan	Ministry of Aircraft Production
Dr S. H. Hollingdale	Ministry of Aircraft Production
Mr J. R. N. Stone	War Office Central Statistical Office
Mr A.W. Taylor	Customs and Excise
Dr Christopherson	Ministry of Home Security
Dr David	Ministry of Home Security
Prof. D. R. Hartree	Ministry of Supply
Dr J. W. Maccoll	Ministry of Supply
Mr J. R. Womersley	Ministry of Supply
Major Gen. G. Cheetham	Ordnance Survey Department
Mr A. W. Mattocks	Treasury
Mr G. F. Peaker	Treasury
Major E. H. Thompson	War Office, Directorate of Military Survey
Dr S. Goldstein	DSIR

[a] Chairman—Sir Charles Darwin

Source: Report on an Interdepartmental Technical Committee. Public Records Office 1944 DSIR 2/204.

The Committee recommended that the Station be staffed by 25 scientific officers and by 50 ancillary staff. The next question was where such an institution should be based. The Committee considered three main points in the choice of a site (all of which were based on earlier suggestions by Darwin to the NPL Executive Committee). The Laboratory should be attached to an intellectual centre, should be conveniently placed for government departments and industry, and should be close to engineering workshops that could be used for the development of new machines.

Cambridge, while offering the benefits of a thriving intellectual centre, was at that time very inconvenient for industry. It was felt that London, although home to many industries and intellectual centres, was short of easily accessible workshop space. The Committee's recommendation was that a new Division be set up at the NPL. Given Darwin's interest in establishing a mathematical and statistical section at the NPL, and his chairmanship of the Committee, this was more or less a foregone conclusion. By July 1944 the NPL Executive Committee approved the proposal, and the search was on for a suitable superintendent.

The appointment of Womersley

There were only two candidates for the post of superintendent of the proposed new Division, Womersley and Sadler, both of whom had sat on the Interdepartmental Technical Committee. Sadler, on paper much the stronger candidate, had been pressed into applying by Darwin, but did not really want to make the move from the Nautical Almanac Office.[14] Womersley had worked with Hartree on the Manchester differential analyser before the war and had set up S. R. 17. He had also, according to his own recollection,[15] read Turing's 'On Computable Numbers'[16] and had already considered the possibility of using telephone relays to build a machine implementing Turing's ideas (see Chapter 3). Womersley indeed made this suggestion to the Interdepartmental Technical Committee.

Womersley was appointed superintendent of the new NPL Mathematics Division in September 1944, but did not take up his post until the following April. In the light of the subsequent electronic computer developments at the NPL, the Mathematics Division might have benefited from the appointment of a more technically able superintendent. But in many other ways Womersley was a good choice. His forte was the political manoeuvring required to set up a new organization. He had the personality needed to address meetings, and the political acumen to court favour in order to push plans through. His friendly relationships with both Darwin and Hartree ensured

Womersley cooperation from the NPL Executive Committee and, crucially, gave him access to information about the then classified computing developments in the United States. It was through Hartree and Darwin that Womersley gained access to the ENIAC during his visit to the United States in spring 1945, and also access to von Neumann's draft report on the EDVAC.[17] Womersley's key role was to show Turing von Neumann's draft report and to recruit Turing for the NPL.

Womersley also did a good job of recruiting other senior staff to the Maths Division. Goodwin, Fox, Olver, Robertson and others came directly from the Admiralty Computing Service, Wilkinson and Vickers came from the

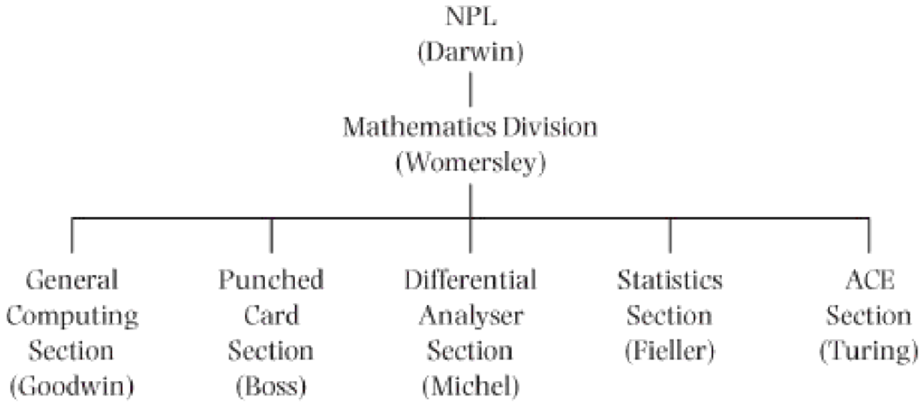

Fig. 1 Organization of the NPL Mathematics Division 1946.

Armaments Research Department at Fort Halstead, and Boss came from the Royal Aircraft Establishment.

Initial structure of the NPL Maths Division

The Mathematics Division was up and running by 1946. It was divided into five sections (see fig. 1). The General Computing Section, headed by Goodwin, was divided into two parts. The first concentrated primarily on numerical analysis and consisted of a strong team of mathematicians, including Fox, Olver, and Wilkinson (part time). The other arm of the General Computing Section was made up of a well-trained junior team of desk calculator operators, led by the experienced Vickers. Vickers and his team carried out many of the computational problems submitted to the Mathematics Division.

The Punched Card Machine Section, initially headed by Boss and his deputy F. Rigg, was staffed predominantly by school leavers trained at the NPL. They worked in groups of up to three, applying Hollerith Punched Card machines to a range of statistical and mathematical jobs for a variety of users. (See the photograph on the following page.) Where necessary the mathematicians of the General Computing Section contributed mathematical methods for use with the machines.

The Differential Analyser Section was headed by Jack Michel and took over the Manchester differential analyser. The staff was quite small and much time was taken up with moving the differential analyser to Teddington (which did not happen until 1948) and also with planning for the installation of a larger machine. The Section took on only a small amount of outside computational work. It did, however, provide an advisory service on all types of analogue computing (including nomograms, harmonic analysers, and differential analysers).

The Hollerith Room in the Babbage Building at the NPL. Turing adopted Hollerith punched-card equipment to provide input/output for the ACE.

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The Statistics Section staff, under E. C. Fieller, ran a statistical service for government and industry. Its role was predominantly advisory, and the service work it did carry out was performed by staff of the General Computing or Punched Card Sections. Its main work was data analysis, production analysis, and quality control analysis. In 1951 the whole section was transferred to the Ministry of Supply.

The ACE Section, established to design and develop a large-scale electronic digital computer, was headed by Turing. Chapter 3 describes the origins and development of the ACE project.

Did the NPL Mathematics Division succeed as a Central Mathematics Station?

The initial organization of the Mathematics Division reflected the proposals of the 1944 Interdepartmental Technical Committee. Did the Maths Division fulfil the expectations of the Technical Committee? This section considers in turn each of the six tasks set by the Committee.

Undertake research into new computing methods and machines. In this the Maths Division was spectacularly successful. The Pilot ACE went into regular service in 1952 and was the first of a series of computer developments undertaken by the Maths Division. The Division also became a leading centre for the new discipline of numerical analysis. Goodwin, Fox, Olver, and Wilkinson all became well-known numerical analysts.

Encourage the development of new computing methods and machines by the dissemination of knowledge. Maths Division staff, and particularly the numerical analysts, published the results of their work widely in leading academic journals (as well as in internal reports). As early as December 1946 Turing gave a series of lectures about the ACE to an invited audience at the Ministry of Supply in London (see Chapter 22, 'The Turing–Wilkinson Lecture Series (1946–7)'). The Maths Division also hosted a computer conference in 1953 to help disseminate knowledge.

Deal with statistical problems arising from industry, the physical sciences, and engineering. Between 1946 and 1951 (when it was transferred to the Ministry of Supply) the Statistics Section dealt with a range of problems. Much of the Section's work was on an advisory level.

Advise on and, if necessary, prepare mathematical tables. The General Computing Section prepared tables for users. In addition, Goodwin and Olver were important members of the Royal Society Mathematical Tables Committee, which prepared and published high quality mathematical tables in the post-war period. They were also involved in discussions concerning the future of mathematical tables in the light of computer developments.[18]

Provide computing services for Government departments, industry, and universities. From the beginning the Punched Card Machine Section and the desk machine arm of the General Computing Section carried out computing work for a very wide variety of clients. In the period 1946–51 the Mathematics Division had approximately 50 users (see Table 2). The scale of the service increased tremendously when the Pilot ACE became available.

Act as a consultant on mathematical and statistical techniques. The Maths Division acted as consultant to many organizations on digital and analogue computing, on statistics, on numerical analysis, on the features of different makes of desk calculators, and on many other topics.

Table 2 NPL Mathematics Division users 1946–51

Admiralty
Armament Research Establishment
AERE, Harwell
Australian National Standards Lab
Bank of England
Birmingham University
Board of Trade
British Cotton Industry Research Association
British Electricity Authority
British Iron and Steel Association
British Railways
British Standards Institute
Building Research Station
Civil Service Commission
Colonial Survey Department
DSIR HQ and 'F' Division
Electrical Research Association
Fuel Research Station
Home Office
Committee on Servo Mechanisms
London Passenger Transport
London University
Manchester University
Mechanical Engineering Research Organization
Medical Research Council
Ministry of Agriculture
Ministry of Civil Aviation
Ministry of Education
Ministry of Health
Ministry of Supply
Ministry of Works
NPL Aerodynamics Division
NPL Metallurgy Division
NPL Metrology Division
NPL Physics Division
NPL Ship Division
Ordnance Survey
Oxford University
Road Research Laboratory
Royal Aircraft Establishment
Royal Society Mathematical Tables Committee
Sir Edward Appleton
Swedish Government Computer Laboratory
Sperry Gyroscope Company
Treasury Training Division
United Steel Companies Ltd.
UCL Statistics Deptartment
War Office

Source: NPL Annual Reports.

Notes

The bulk of the research for this chapter was carried out as part of a 1986 Ph.D. thesis while I was in receipt of a grant from the Science and Engineering Research Council. I would like to thank the many ex-

employees of the Admiralty Computing Service and the NPL Mathematics Division, including E. T. Goodwin, D. H. Sadler, J. Todd, T. Vickers, M. Woodger, and many more, who have patiently answered my questions and put me straight on a number of things. Thanks also to Jack Copeland for his editorial work on the chapter.

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3 *The origins and development of the ACE project*

B. Jack Copeland

Womersley and Turing join the NPL

The name 'Automatic Computing Engine' was due to Womersley[1] and the story of the ACE begins with his appointment as superintendent of the newly created Mathematics Division of the National Physical Laboratory (see the previous chapter).[2] 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'.[3]

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'.[4] 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'.[5]

In December 1944 Womersley addressed the Executive Committee of the NPL on the potential of electronic computing. 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.[6]

In November 1946 Womersley wrote a 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.[7]
> Late 1943 J.R.W. first heard of these American machines.

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.

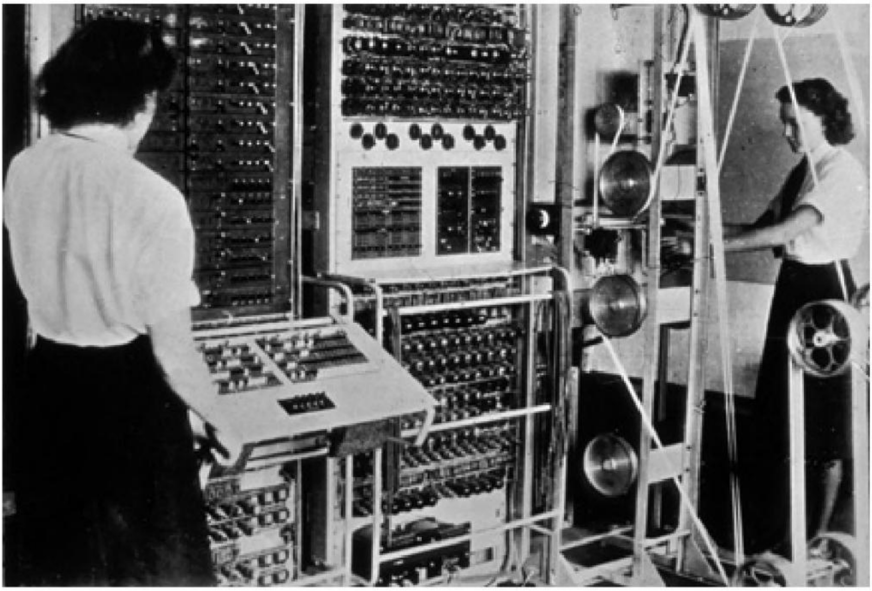
1944 Oct. J.R.W. prepares research programme for Maths. Division which includes an item covering the A.C.E.

1944 Nov.[8] 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 …'

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.[9]

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 realized. While Womersley clearly understood the importance of Turing's pre-war article 'On computable numbers, with an application to the Entscheidungsproblem'—the birthplace of the stored-program concept—he was completely unaware of the highly secret developments in electronic computing that had taken place during the war at Bletchley Park (headquarters of the codebreaking organization known as the Government Code and Cypher School). At Bletchley Park Turing was among the few who knew of Colossus, the first large-scale electronic digital computer (see Chapter 5, 'Turing and the Computer'). Designed by Thomas Flowers, Colossus made its first successful codebreaking runs at Bletchley Park in December 1943 (two years before the American ENIAC was operational). Once Turing had seen Colossus it was, according to Flowers, just a matter of his waiting for an opportunity to put the ideas of his 1936 article into practice.[10] Probably Turing did not need much persuasion to join Mathematics Division.



Colossus at Bletchley Park.

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Proposed electronic calculator

Turing's employment commenced on 1 October 1945, by which time Mathematics Division was 'functioning on a limited scale'.[11] 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'.[12] 'Proposed Electronic Calculator' contained the first relatively complete specification of an electronic stored-program digital computer (see the Introduction to this book).

The 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. Womersley wrote to Darwin:

> <u>"ACE" Machine Project.</u>
>
> 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. 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 as 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.[13] …

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.[14]

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 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.

> 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 useable form.[51]

In a letter written in 1972 Williams described in some detail what he and Kilburn were told by Newman:

> 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 was the simplest embodiment of these principles, with the sole difference that it used a subtracting rather than an adding accumulator.[52]

Turing's early input to the developments at Manchester, hinted at by Williams in his above-quoted reference to Turing, may have been via the lectures on computer design that Turing and Wilkinson gave in London during the period December 1946 to February 1947 (see Chapter 22, 'The Turing–Wilkinson Lecture Series'). The lectures were attended by representatives of various organizations planning to use or build an electronic computer. Kilburn was in the audience.[53] (Kilburn usually said, when asked from where he obtained his basic knowledge of the computer, that he could not remember;[54] e.g., 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'.[55])

Whatever role Turing's lectures may have played in informing Kilburn, there is little doubt that credit for the Manchester computer—called the 'Newman–Williams machine' by Huskey in a report written shortly after his visit in 1947 to the Manchester project (see Chapter 23, 'The State of the Art in Electronic Digital Computing in Britain and the United States')—belongs not only to Williams and Kilburn but also to Newman, and that the influence on Newman of Turing's 1936 paper was crucial (as was the influence of Flowers' Colossus).

The Manchester computer and the EDVAC

The Baby and the Manchester Mark I are sometimes said to have descended from the EDVAC (see, e.g., the American *Family Tree of Computer Design*, fig. 1 in Chapter 6). Newman was well aware of von Neumann's 'First Draft of a Report on the EDVAC'. In the summer of 1946 he sent David Rees, a lecturer in his department at Manchester and an ex-member of the Newmanry (Newman's section at Bletchley Park), to a series of lectures at the Moore School, where Eckert, Mauchly, and other members of the ENIAC–EDVAC group publicized their ideas on computer design.[56] In the autumn of 1946 Newman himself went to Princeton for three months.[57]

Newman's advocacy of 'a central accumulator'—a characteristic feature of the EDVAC but not of the ACE—was probably influenced by his knowledge of the American proposals. However, von Neumann's ideas seem to have had little influence on other members of the Manchester project. Kilburn spoke scathingly of the von Neumann 'dictat'.[58] Tootill said:

> 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'.[59]

> 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, because I think he was in general quite punctilious in acknowledging other people's ideas.[60]

Tootill added:

> 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 I, I got them to approve the list of functions.[61]

Index