Alan Turing

compiled by Geoff Wilkins

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Alan Turing

“Turing” redirects here. For other uses, see Turing (disambiguation).

Alan Mathison Turing OBE FRS (/ˈtjʊərɪŋ/; 23 June 1912 – 7 June 1954) was a British pioneering computer scientist, mathematician, logician, cryptanalyst and theoretical biologist. He was highly influential in the development of computer science, providing a formalisation of the concepts of algorithm and computation with the Turing machine, which can be considered a model of a general purpose computer.[2][3][4] Turing is widely considered to be the father of theoretical computer science and artificial intelligence.[5]

During the Second World War, Turing worked for the Government Code and Cypher School (GC&CS) at Bletchley Park, Britain’s codebreaking centre. For a time he led Hut 8, the section responsible for German naval cryptanalysis. He devised a number of techniques for breaking German ciphers, including improvements to the pre-war Polish bombe method and an electromechanical machine that could find settings for the Enigma machine. Turing played a pivotal role in cracking intercepted coded messages that enabled the Allies to defeat the Nazis in many crucial engagements, including the Battle of the Atlantic; it has been estimated that this work shortened the war in Europe by as many as two to four years.[6]

After the war, he worked at the National Physical Laboratory, where he designed the ACE, among the first designs for a stored-program computer. In 1948 Turing joined Max Newman's Computing Laboratory at the University of Manchester, where he helped develop the Manchester computers[7] and became interested in mathematical biology. He wrote a paper on the chemical basis of morphogenesis, and predicted oscillating chemical reactions such as the Belousov–Zhabotinsky reaction, first observed in the 1960s.

Turing was prosecuted in 1952 for homosexual acts, whensuchbehaviourwasstillacriminalactintheUK.He accepted treatment with DES (chemical castration) as an alternative to prison. Turing died in 1954, 16 days before his 42nd birthday, from cyanide poisoning. An inquest determined his death as suicide, but it has been noted that the known evidence is equally consistent with accidental poisoning.[8] In 2009, following an Internet campaign, British Prime Minister Gordon Brown made an official public apology on behalf of the British government for “the appalling way he was treated”. Queen Elizabeth II granted him a posthumous pardon in 2013.[9][10][11]

1.1 Early life and family

Turing was born in Maida Vale, London, while his father, Julius Mathison Turing (1873–1947), was on leave from his position with the Indian Civil Service (ICS) at Chhatrapur, Bihar and Orissa Province, in British India.[12][13] Turing’s father was the son of a clergyman, the Rev. John Robert Turing, from a Scottish family of merchants which had been based in the Netherlands and included a baronet. Turing’s mother, Julius’ wife, was Ethel Sara (née Stoney; 1881–1976), daughter of Edward Waller Stoney, chief engineer of the Madras Railways. The Stoneys were a Protestant Anglo-Irish gentry family from both County Tipperary and County Longford, while Ethel herself had spent much of her childhood in County Clare.[14]

Julius’ work with the ICS brought the family to British India, where his grandfather had been a general in the Bengal Army. However, both Julius and Ethel wanted their children to be brought up in Britain, so they moved to Maida Vale,[15] London, where Turing was born on 23 June 1912, as recorded by a blue plaque on the outside of the house of his birth,[16][17] later the Colonnade Hotel.[12][18] He had an elder brother, John (the father of Sir John Dermot Turing, 12th Baronet of the Turing baronets).

Turing’s father’s civil service commission was still active and during Turing’s childhood years Turing’s parents travelled between Hastings in England[19] and India, leaving their two sons to stay with a retired Army couple. At Hastings, Turing stayed at Baston Lodge, Upper Maze Hill, St Leonards-on-Sea, now marked with a blue plaque.[20]

Very early in life, Turing showed signs of the genius that he was later to display prominently.[21] His parents purchased a house in Guildford in 1927, and Turing lived

there during school holidays. The location is also marked with a blue plaque.[22]

1.2 Education

1.2.1 School

Turing'sparentsenrolledhimatStMichael's, adayschool at 20 Charles Road, St Leonards-on-Sea, at the age of six. The headmistress recognised his talent early on, as did many of his subsequent educators. In 1926, at the age of 13, he went on to Sherborne School, an independent school in the market town of Sherborne in Dorset. The first day of term coincided with the 1926 General Strike in Britain, but he was so determined to attend that he rode his bicycle unaccompanied more than 60 miles (97 km) from Southampton to Sherborne, stopping overnight at an inn.[23]

Turing's natural inclination towards mathematics and science did not earn him respect from some of the teachers at Sherborne, whose definition of education placed more emphasis on the classics. His headmaster wrote to his parents: "I hope he will not fall between two stools. If he is to stay at public school, he must aim at becoming *educated*. If he is to be solely a *Scientific Specialist*, he is wasting his time at a public school".[24] Despite this, Turing continued to show remarkable ability in the studies he loved, solving advanced problems in 1927 without having studied even elementary calculus. In 1928, aged 16, Turing encountered Albert Einstein's work; not only did he grasp it, but it is possible that he managed to deduce Einstein's questioning of Newton's laws of motion from a text in which this was never made explicit.[25]

At Sherborne, Turing formed a significant friendship with fellow pupil Christopher Morcom, who has been described as Turing's "first love". Their relationship provided inspiration in Turing's future endeavours, but it was cut short by Morcom's death, in February 1930, from complications of bovine tuberculosis, contracted after drinking infected cow's milk some years previously.[26][27][28]

The event caused Turing great sorrow. He coped with his griefbyworkingthatmuchharderonthetopicsofscience and mathematics that he had shared with Morcom. In a letter to Morcom's mother Turing said:

> I am sure I could not have found anywhere another companion so brilliant and yet so charming and unconceited. I regarded my interest in my work, and in such things as astronomy (to which he introduced me) as something to be shared with him and I think he felt a little the same about me ... I know I must put as much energy if not as much interest into my work as if he were alive, because that is what he would like me to do.[29]

Some have speculated that Morcom's death was the cause of Turing's atheism and materialism,[30] but this seems unlikely. Apparently, at this point in his life he still believed in such concepts as a spirit, independent of the body and surviving death. In a later letter, also written to Morcom's mother, Turing said:

> Personally, I believe that spirit is really eternally connected with matter but certainly not by the same kind of body ... as regards the actual connection between spirit and body I consider that the body [can] hold on to a 'spirit', whilst the body is alive and awake the two are firmly connected. When the body is asleep I cannot guess what happens but when the body dies, the 'mechanism' of the body, holding the spirit is gone and the spirit finds a new body sooner or later, perhaps immediately.[31]

1.2.2 University and work on computability

After Sherborne, Turing studied as an undergraduate from 1931 to 1934 at King's College, Cambridge, whence he gained first-class honours in mathematics. In 1935, at the age of 22, he was elected a fellow of King's on the strength of a dissertation in which he proved the central limit theorem,[32] despite the fact that the committee had failed to identify that it had already been proven, in 1922, by Jarl Waldemar Lindeberg.[33]

In1928, GermanmathematicianDavidHilberthadcalled attention to the *Entscheidungsproblem* (decision problem). In his paper "On Computable Numbers, with an Application to the *Entscheidungsproblem*" (submitted on 28 May 1936 and delivered 12 November),[34] Turing reformulated Kurt Gödel's 1931 results on the limits of proof and computation, replacing Gödel's universal arithmetic-based formal language with the formal and simple hypothetical devices that became known as Turing machines. He proved that some such machine would be capable of performing any conceivable mathematical computation if it were representable as an algorithm. He went on to prove that there was no solution to the *Entscheidungsproblem* by first showing that the halting problem for Turing machines is undecidable: in general, it is not possible to decide algorithmically whether a given Turing machine will ever halt.

Although Turing's proof was published shortly after Alonzo Church's equivalent proof[35] using his lambda calculus, Turing's approach is considerably more accessible and intuitive than Church's. It also included a notion of a 'Universal Machine' (now known as a universal Turingmachine), withtheideathatsuchamachinecouldperform the tasks of any other computation machine (as indeed could Church's lambda calculus). According to the

King's College, Cambridge, where Turing was a student in 1931 and became a Fellow in 1935. The computer room is named after him.

Church–Turing thesis, Turing machines and the lambda calculus are capable of computing anything that is computable. John von Neumann acknowledged that the central concept of the modern computer was due to Turing's paper.[36] To this day, Turing machines are a central object of study in theory of computation.

From September 1936 to July 1938, Turing spent most of his time studying under Church at Princeton University. In addition to his purely mathematical work, he studied cryptology and also built three of four stages of an electro-mechanical binary multiplier.[37] In June 1938, he obtained his PhD from Princeton;[38] his dissertation, *Systems of Logic Based on Ordinals*,[39][40] introduced the concept of ordinal logic and the notion of relative computing, where Turing machines are augmented with socalled oracles, allowing a study of problems that cannot be solved by a Turing machine.

When Turing returned to Cambridge, he attended lectures given in 1939 by Ludwig Wittgenstein about the foundations of mathematics.[41] Remarkably, the lectures have been reconstructed verbatim, including interjections from Turing and other students, from students' notes.[42] Turing and Wittgenstein argued and disagreed, with Turing defending formalism and Wittgenstein propounding his view that mathematics does not discover any absolute truths but rather invents them.[43]

1.3 Cryptanalysis

During the Second World War, Turing was a leading participant in the breaking of German ciphers at Bletchley Park. The historian and wartime codebreaker Asa Briggs has said, "You needed exceptional talent, you needed genius at Bletchley and Turing's was that genius."[44] From September 1938, Turing had been working part-time with the GC&CS, the British code breaking organisation. He concentrated on cryptanalysis of the Enigma, with Dilly Knox, a senior GC&CS codebreaker.[45] Soon after the July 1939 Warsaw meeting at which the Polish Cipher Bureau had provided the British and French with the details of the wiring of Enigma rotors and their method of decrypting Enigma code messages, Turing and Knox started to work on a less fragile approach to the problem.[46] The Polish method relied on an insecure indicator procedure that the Germans were likely to change, which they did in May 1940. Turing's approach was more general, using crib-based decryption for which he produced the functional specification of the bombe (an improvement of the Polish Bomba).[47]

Two cottages in the stable yard at Bletchley Park. Turing worked here in 1939 and 1940, before moving to Hut 8.

On 4 September 1939, the day after the UK declared war on Germany, Turing reported to Bletchley Park, the wartime station of GC&CS.[48] Specifying the bombe was the first of five major cryptanalytical advances that Turing made during the war. The others were: deducing the indicator procedure used by the German navy; developing a statistical procedure for making much more efficient use of the bombes dubbed *Banburismus*; developing a procedure for working out the cam settings of the wheelsoftheLorenzSZ40/42(*Tunny*)dubbed *Turingery* and, towards the end of the war, the development of a portablesecurevoicescrambleratHanslopeParkthatwas codenamed *Delilah*.

By using statistical techniques to optimise the trial of different possibilities in the code breaking process, Turing made an innovative contribution to the subject.

He wrote two papers discussing mathematical approaches which were entitled *The Applications of Probability to Cryptography*[49] and *Paper on Statistics of Repetitions*,[50] which were of such value to GC&CS and its successor GCHQ that they were not released to the UK National Archives until April 2012, shortly before the centenary of his birth. A GCHQ mathematician said at the time that the fact that the contents had been restricted for some 70 years demonstrated their importance.[51]

Turing had something of a reputation for eccentricity at Bletchley Park. He was known to his colleagues as 'Prof' and his treatise on Enigma was known as 'The Prof's Book'.[52] Jack Good, a cryptanalyst who worked with him, is quoted by Ronald Lewin as having said of Turing:

> In the first week of June each year he would get a bad attack of hay fever, and he would cycle to the office wearing a service gas mask to keep the pollen off. His bicycle had a fault: the chain would come off at regular intervals. Instead of having it mended he would count the number of times the pedals went round and would get off the bicycle in time to adjust the chain by hand. Another of his eccentricities is that he chained his mug to the radiator pipes to prevent it being stolen.[53]

While working at Bletchley, Turing, who was a talented long-distance runner, occasionally ran the 40 miles (64 km) to London when he was needed for high-level meetings,[54] and he was capable of world-class marathon standards.[55][56] Turing tried out for the 1948 British Olympic team, hampered by an injury. His tryout time for the marathon was only 11 minutes slower than British silver medalist Thomas Richards' Olympic race time of 2 hours 35 minutes. He was Walton Athletic Club's best runner, a fact discovered when he passed the group while running alone.[57][58][59]

In 1945, Turing was awarded the OBE by King George VI for his wartime services, but his work remained secret for many years.[60]

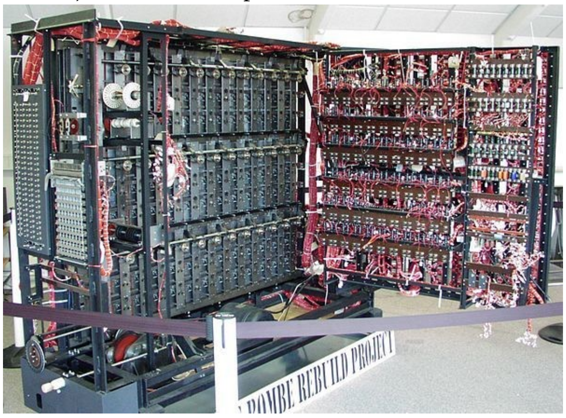
1.3.1 Bombe

WithinweeksofarrivingatBletchleyPark,[48] Turinghad specified an electromechanical machine that could help break Enigma more effectively than the Polish *bomba kryptologiczna*, from which its name was derived. The bombe, with an enhancement suggested by mathematician Gordon Welchman, became one of the primary tools, and the major automated one, used to attack Enigma-enciphered messages.

Jack Good opined:

> Turing's most important contribution, I *think*, was of part of the design of the bombe, the cryptanalytic machine. He had the idea that you could use, in effect, a theorem in logic which sounds, to the untrained ear, rather absurd; namely that, from a contradiction, you can deduce *everything*.[61]

The bombe searched for possible correct settings used for an Enigma message (i.e., rotor order, rotor settings and plugboard settings), using a suitable *crib*: a fragment of probable plaintext. For each possible setting of the rotors (which had on the order of 10^{19} states, or 10^{22} states for the four-rotor U-boat variant),[62] the bombe performed



A complete and working replica of a bombe at the National Codes
Centre at Bletchley Park

a chain of logical deductions based on the crib, implemented electrically. The bombe detected when a contradiction had occurred, and ruled out that setting, moving on to the next. Most of the possible settings would cause contradictions and be discarded, leaving only a few to be investigated in detail. The first bombe was installed on 18 March 1940.[63]

By late 1941, Turing and his fellow cryptanalysts Gordon Welchman, Hugh Alexander, and Stuart Milner-Barry were frustrated. Building on the work of the Poles, they had set up a good working system for decrypting Enigma signals but they only had a few people and a few bombes so they did not have time to translate all the signals. In the summer they had had considerable success and shipping losses had fallen to under 100,000 tons a month but they were still on a knife-edge. They badly needed more resources to keep abreast of German adjustments. They had tried to get more people and fund more bombes through the proper channels but they were getting nowhere. Finally, breaking all the rules, on 28 October they wrote directly to Winston Churchill spelling out their difficulties, with Turing as the first named. They emphasised how small their need was compared with the vast expenditure of men and money by the forces and compared with the level of assistance they could offer to the forces.[64]

As Andrew Hodges, biographer of Turing, later wrote, “This letter had an electric effect.”[65] Churchill wrote a memo to General Ismay which read: “ACTION THIS DAY. Make sure they have all they want on extreme priority and report to me that this has been done.” On 18 November, the chief of the secret service reported that every possible measure was being taken.[65] The cryptographers at Bletchley Park did not know of the prime minister’s response, but as Milner-Barry later recalled, “All that we did notice was that almost from that day the rough ways began miraculously to be made smooth.”[66] More than two hundred bombes were in operation by the end of the war.[67]

1.3.2 Hut 8 and Naval Enigma

Turing by Stephen Kettle at Bletchley Park, commissioned by Sidney Frank, built from half a million pieces of Welsh slate.[68]

Turing decided to tackle the particularly difficult problem of German naval Enigma “because no one else was doing anything about it and I could have it to myself”.[69] In December 1939, Turing solved the essential part of the naval indicator system, which was more complex than the indicator systems used by the other services.[69][70] That same night he also conceived of the idea of *Banburismus*, a sequential statistical technique (what Abraham Wald later called sequential analysis) to assist in breaking naval Enigma, “though I was not sure that it wouldwork in practice, and was not, in fact, sure until some days had actually broken.” [69] For this, he invented a measure of weight of evidence that he called the *ban*. Banburismus could rule out certain sequences of the Enigma rotors, substantially reducing the time needed to test settings on the bombes.

In 1941, Turing proposed marriage to Hut 8 colleague JoanClarke, afellowmathematicianandcryptanalyst, but their engagement was short-lived. After admitting his homosexuality to his fiancée, who was reportedly “unfazed” by the revelation, Turing decided that he could not go through with the marriage.[71]

Turing travelled to the United States in November 1942[74] and worked with US Navy cryptanalysts on naval Enigma and bombe construction in Washington; he also visited their Computing Machine Laboratory in Dayton, Ohio. His reaction to the American bombe design was far from enthusiastic:

> It seems a pity for them to go out of their way to build a machine to do all this stopping if it is not necessary. I am now converted to the extent of thinking that, starting from scratch

Joan Clarke, friend and colleague of Turing at Hut 8, to whom he proposed marriage in the spring of 1941[72][73]

> on the design of a bombe, this method is about as good as our own. The American bombe

> program was to produce 336 bombes, one for each wheel order. I used to smile inwardly at the conception of test (of commutators) can hardly be considered conclusive, as they were not testing for the bounce with electronic stop finding devices.[75]
>
> — Alan Turing

During this trip, he also assisted at Bell Labs with the development of secure speech devices.[76] He returned to Bletchley Park in March 1943. During his absence, Hugh Alexander had officially assumed the position of head of Hut 8, although Alexander had been *de facto* head for some time (Turing had little interest in the day-to-day running of the section). Turing became a general consultant for cryptanalysis at Bletchley Park.

Alexander wrote as follows about his contribution:

> There should be no question in anyone's mind that Turing's work was the biggest factor in Hut 8's success. In the early days, he was the only cryptographer who thought the problem worth tackling and not only was he primarily responsible for the main theoretical work within the Hut, but he also shared with Welchman and Keen the chief credit for the invention of the bombe. It is always difficult to say that anyone is 'absolutely indispensable', but if anyone was indispensable to Hut 8, it was Turing. The pioneer's work always tends to be forgotten when experience and routine later make everything seem easy and many of us in Hut 8 felt that the magnitude of Turing's contribution was never fully realised by the outside world.[77]
>
> — Hugh Alexander

1.3.3 Turingery

In July 1942, Turing devised a technique termed *Turingery* (or jokingly *Turingismus*)[78] for use against the Lorenz cipher messages produced by the Germans' new *Geheimschreiber* (secret writer) machine. This was a teleprinter rotor cipher attachment codenamed *Tunny* at Bletchley Park. Turingery was a method of *wheelbreaking*, i.e., a procedure for working out the cam settings of Tunny's wheels.[79] He also introduced the Tunny team to Tommy Flowers who, under the guidance of Max Newman, went on to build the Colossus computer, the world's first programmable digital electronic computer, which replaced a simpler prior machine (the Heath Robinson), and whose superior speed allowed the statistical decryption techniques to be applied usefully to the messages.[80] Some have mistakenly said that Turing was a key figure in the design of the Colossus computer. Turingery and the statistical approach of Banburismus undoubtedly fed into the thinking about cryptanalysis of the Lorenz cipher,[81][82] but he was not directly involved in the Colossus development.[83]

1.3.4 Delilah

Following his work at Bell Labs in the US,[84] Turing pursued the idea of electronic enciphering of speech in the telephone system, and in the latter part of the war, he moved to work for the Secret Service's Radio Security Service (later HMGCC) at Hanslope Park. There he further developed his knowledge of electronics with the assistance of engineer Donald Bayley. Together they undertook the design and construction of a portable secure voice communications machine codenamed *Delilah*.[85] It was intended for different applications, lacking capability for use with long-distance radio transmissions, and in any case, Delilah was completed too late to be used during the war. Though the system worked fully, with Turing demonstrating it to officials by encrypting and decrypting a recording of a Winston Churchill speech, Delilah was not adopted for use.[86]

Turing also consulted with Bell Labs on the development of SIGSALY, a secure voice system that was used in the later years of the war.

1.4 Early computers and the Turing test

Plaque, 78 High Street, Hampton

From 1945 to 1947, Turing lived in Hampton, London[87] while he worked on the design of the ACE (Automatic Computing Engine) at the National Physical Laboratory (NPL). He presented a paper on 19 February 1946, which was the first detailed design of a stored-program computer.[88] Von Neumann's incomplete *First Draft of a Report on the EDVAC* had predated Turing's paper, but it was much less detailed and, according to John R. Womersley, Superintendent of the NPL Mathematics Division, it "contains a number of ideas which are Dr. Turing's own".[89] Although ACE was a feasible design, the secrecy surrounding the wartime work at Bletchley Park led to delays in starting the project and he became disillusioned. In late 1947 he returned to Cambridge for a sabbatical year during which he produced a seminal work on *Intelligent Machinery* that was not published in his lifetime.[90] While he was at Cambridge, the Pilot ACE was being built in his absence. It executed its first program on 10 May 1950, and a number of later computers around the world owe much to it, including the English Electric DEUCE and the American Bendix G-15. The full version of Turing's ACE was not built until after his death.[91]

According to the memoirs of the German computer pioneer Heinz Billing from the Max Planck Institute for Physics, published by Genscher, Düsseldorf, there was a meeting between Alan Turing and Konrad Zuse.[92] It took place in Göttingen in 1947. The interrogation had the form of a colloquium. Participants were Womersley, Turing, Porter from England and a few German researchers like Zuse, Walther, and Billing. (For more details see Herbert Bruderer, *Konrad Zuse und die Schweiz*). In 1948 Turing was appointed Reader in the Mathematics

Department at the University of Manchester. In 1949, he became Deputy Director of the Computing Laboratory there, working on software for one of the earliest storedprogramme computers—the Manchester Mark 1. During this time he continued to do more abstract work in mathematics,[93] and in "Computing Machinery and Intelligence" (*Mind*, October 1950), Turing addressed the problem of artificial intelligence, and proposed an experiment which became known as the Turing test, an attempt to define a standard for a machine to be called "intelligent". The idea was that a computer could be said to "think" if a human interrogator could not tell it apart, through conversation, from a human being.[94] In the paper, Turing suggested that rather than building a programme to simulate the adult mind, it would be better rather to produce a simpler one to simulate a child's mind and then to subject it to a course of education. A reversed form of the Turing test is widely used on the Internet; the CAPTCHAtestisintendedtodeterminewhethertheuser is a human or a computer.

In 1948 Turing, working with his former undergraduate colleague, D. G. Champernowne, began writing a chess program for a computer that did not yet exist. By 1950, the programme was completed and dubbed the Turochamp.[95] In 1952, he tried to implement it on a Ferranti Mark 1, but lacking enough power, the computer was unable to execute the programme. Instead, Turing playeda gameinwhichhesimulatedthecomputer, taking about half an hour per move. The game was recorded.[96] The program lost to Turing's colleague Alick Glennie, although it is said that it won a game against Champernowne's wife.

His Turing test was a significant, characteristically provocative and lasting contribution to the debate regarding artificial intelligence, which continues after more than half a century.[97]

He also invented the LU decomposition method in 1948,[93] used today for solving matrix equations.[98]

1.5 Pattern formation and mathematical biology

Towards the end of his life, Turing turned to mathematical biology, publishing the "The Chemical Basis of Morphogenesis" in 1952. He was interested in morphogenesis, the development of patterns and shapes in biological organisms. His central interest in the field was understanding Fibonacci phyllotaxis, the existence of Fibonacci numbers in plant structures.[99] He suggested that a system of chemicals reacting with each other and diffusing across space, termed a reactiondiffusion system, could account for "the main phenomena of morphogenesis."[100] Instability in the system of partial differential equations used to model the system allows for small random perturbations to homogeneous initial state to drive the development of patterns. Though published before even the structure or role of DNA was understood, Turing's work on morphogenesis remains relevant today, and is considered a seminal piece of work in mathematical biology.[101] Experiments suggest that Turing's work can partially explain growth of "feathers, hair follicles, the branching pattern of lungs, and even the left-right asymmetry that puts the heart on the left side of the chest."[102] In 2012, Sheth, et al. found that in mice, removal of Hox genes causes an increase in the number of digits without an increase in the overall size of the limb, suggesting that Hox genes control digit formation by tuning the wavelength of a Turing-type mechanism.[103] Later papers, though promised, were not available until *Collected Works of A. M. Turing* was published in 1992.[104]

1.6 Conviction for indecency

In January 1952, Turing, then 39, started a relationship with Arnold Murray, a 19-year-old unemployed man. Turing had met Murray just before Christmas outside the Regal Cinema when walking down Manchester's Oxford Road and invited him to lunch. On 23 January Turing's house was burgled. Murray told Turing that the burglar was an acquaintance of his, and Turing reported the crime to the police. During the investigation he acknowledged a sexual relationship with Murray. Homosexual acts were criminal offences in the United Kingdom at that time,[105] and both men were charged with gross indecency under Section 11 of the Criminal Law Amendment Act 1885.[106] Initial committal proceedings for the trial were held on 27 February during which Turing's solicitor "reserved his defence".

Later, convinced by the advice of his brother and his own solicitor, Turing entered a plea of guilty.[107] The case, *Regina v. Turing and Murray,* was brought to trial on 31 March 1952,[108] when Turing was convicted and given a choice between imprisonment and probation, which would be conditional on his agreement to undergo hormonal treatment designed to reduce libido. He accepted the option of treatment via injections of stilboestrol, a synthetic oestrogen; this treatment was continued for the course of one year. The treatment rendered Turing impotent and caused gynaecomastia,[109] fulfilling in the literal sense Turing's prediction that "no doubt I shall emerge from it all a different man, but quite who I've not found out".[110][111] Murray was given a conditional discharge.[112]

Turing's conviction led to the removal of his security clearance and barred him from continuing with his cryptographic consultancy for the Government Communications Headquarters (GCHQ), the British signals intelligence agency that had evolved from GC&CS in 1946 (though he kept his academic job). He was denied entry into the United States after his conviction in 1952, but was free to visit other European countries, even though this was viewed by some as a security risk. At the time, there was acute public anxiety about homosexual entrapment of spies by Soviet agents,[113] because of the recent exposure of the first two members of the Cambridge Five, Guy Burgess and Donald Maclean, as KGB double agents. Turing was never accused of espionage, but in common with all who had worked at Bletchley Park, he was prevented by the Official Secrets Act from discussing his war work.[114]

1.7 Death

On 8 June 1954, Turing's housekeeper found him dead. He had died the previous day. A post-mortem examination established that the cause of death was cyanide poisoning. When his body was discovered, an apple lay half-eaten beside his bed, and although the apple was not tested for cyanide,[115] it was speculated that this was the means by which a fatal dose was consumed. An inquest determined that he had committed suicide, and he was cremated at Woking Crematorium on 12 June 1954.[116] Turing's ashes were scattered there, just as his father's had been.

1.7.1 Alternative death theories

Philosophy professor Jack Copeland has questioned various aspects of the coroner's historical verdict, suggesting the alternative explanation of the accidental inhalation of cyanide fumes from an apparatus for gold electroplating spoons, using potassium cyanide to dissolve the gold, which Turing had set up in his tiny spare room. Copeland notes that the autopsy findings were more consistent with inhalation than with ingestion of the poison. Turing also habitually ate an apple before bed, and it was not unusual for it to be discarded half-eaten.[117] In addition, Turing had reportedly borne his legal setbacks and hormone treatment (which had been discontinued a year previously) "with good humour" and had shown no sign of despondency prior to his death, setting down, in fact, a list of tasks he intended to complete upon return to his office after the holiday weekend.[117] At the time, Turing's mother believed that the ingestion was accidental, resulting from her son's careless storage of laboratory chemicals.[118] Biographer Andrew Hodges suggests that Turing may have arranged the cyanide experiment deliberately, to give his mother some plausible deniability.[119]

Andrew Hodges, and another biographer, David Leavitt, have both suggested that Turing was re-enacting a scene from the Walt Disney film *Snow White and the Seven Dwarfs* (1937), his favourite fairy tale, both noting that (in Leavitt's words) he took "an especially keen pleasure in the scene where the Wicked Queen immerses her apple in the poisonous brew".[120]

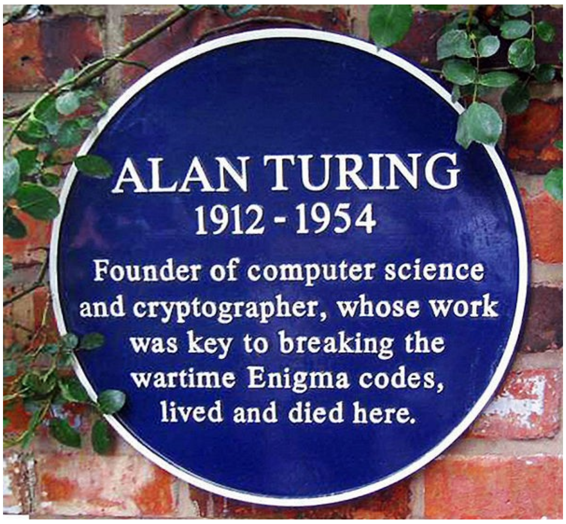
1.8 Recognition and tributes

A biography published by the Royal Society shortly after Turing's death, while his wartime work was still subject to the Official Secrets Act, recorded:

> Three remarkable papers written just before the war, on three diverse mathematical

subjects, show the quality of the work that might have been produced if he had settled down to work on some big problem at that critical time. For his work at the Foreign Office he was awarded the OBE.[2]

Since 1966, the Turing Award has been given annually by the Association for Computing Machinery (ACM) for technical or theoretical contributions to the computing community. It is widely considered to be the computing world's highest honour, equivalent to the Nobel Prize.[121]



A blue plaque marking Turing's home at Wilmslow, Cheshire

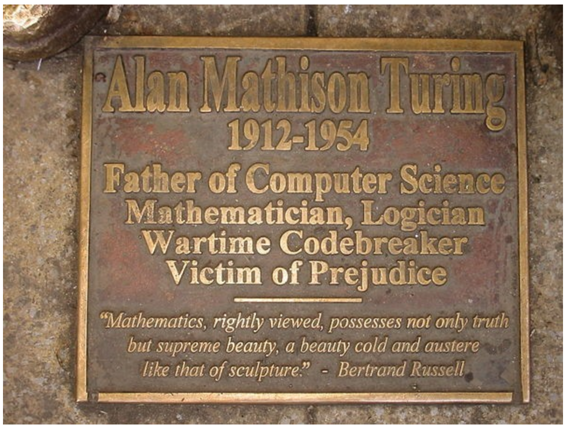
On 23 June 1998, on what would have been Turing's 86th birthday, his biographer, Andrew Hodges, unveiled an official English Heritage blue plaque at his birthplace and childhood home in Warrington Crescent, London, later the Colonnade Hotel.[122][123] To mark the 50th anniversary of his death, a memorial plaque was unveiled on 7 June 2004 at his former residence, Hollymeade, in Wilmslow, Cheshire.[124]

On 13 March 2000, Saint Vincent and the Grenadines issued a set of postage stamps to celebrate the greatest achievements of the 20th century, one of which carries a portrait of Turing against a background of repeated 0s and 1s, and is captioned: "1937: Alan Turing's theory of digital computing". On 1 April 2003, Turing's work at Bletchley Park was named an IEEE Milestone.[125] On 28 October 2004, a bronze statue of Alan Turing sculpted by John W. Mills was unveiled at the University of Surrey in Guildford, marking the 50th anniversary of Turing's death; it portrays him carrying his books across the

campus.[126] In 2006, Boston Pride named Turing their Honorary Grand Marshal.[127]

Turing was one of four mathematicians examined in the BBC documentary entitled *Dangerous Knowledge* (2008).[128] The *Princeton Alumni Weekly* named Turing the second most significant alumnus in the history of Princeton University, second only to President James Madison. A 1.5-ton, life-size statue of Turing was unveiled on 19 June 2007 at Bletchley Park. Built from approximately half a million pieces of Welsh slate, it was sculpted by Stephen Kettle, having been commissioned by the American billionaire Sidney Frank.[129]

Turing has been honoured in various ways in Manchester, the city where he worked towards the end of his life. In 1994, a stretch of the A6010 road (the Manchester city intermediate ring road) was named "Alan Turing Way". A bridge carrying this road was widened, and carries the name Alan Turing Bridge. A statue of Turing was unveiled in Manchester on 23 June 2001 in Sackville Park, between the University of Manchester building on Whitworth Street and Canal Street. The memorial statue depicts the "father of Computer Science" sitting on a bench at a central position in the park. Turing is shown holding an apple. The cast bronze bench carries in relief the text 'Alan Mathison Turing 1912–1954', and the motto 'Founder of Computer Science' as it could appear if encoded by an Enigma machine: 'IEKYF ROMSI ADXUO KVKZC GUBJ'.



Turing memorial statue plaque in Sackville Park, Manchester

A plaque at the statue's feet reads 'Father of computer science, mathematician, logician, wartime codebreaker, victim of prejudice'. There is also a Bertrand Russell quotation saying 'Mathematics, rightly viewed, possesses not only truth, but supreme beauty — a beauty cold and austere, like that of sculpture.' The sculptor buried his own old Amstrad computer under the plinth as a tribute to "the godfather of all modern computers".[130]

In 1999, *Time Magazine* named Turing as one of the 100 Most Important People of the 20th century and stated: "The fact remains that everyone who taps at a keyboard, opening a spreadsheet or a word-processing program, is working on an incarnation of a Turing machine.”[3] Turing is featured in the Neal Stephenson novel *Cryptonomicon* (1999).

In 2002, a new building named after Alan Turing was constructed on the Malvern site of QinetiQ. It houses about 200 scientists and engineers, some of whom work on big data computing.

In 2002, Turing was ranked twenty-first on the BBC nationwide poll of the 100 Greatest Britons.[131] In 2006 British writer and mathematician Ioan James chose Turing as one of twenty people to feature in his book about famous historical figures who may have had some of the traits of Asperger syndrome.[132] In 2010, actor/playwright Jade Esteban Estrada portrayed Turing in the solo musical, *ICONS: The Lesbian and Gay History of the World, Vol. 4*. In 2011, in *The Guardian's* “My hero” series, writer Alan Garner chose Turing as his hero and described how they had met whilst out jogging in the early 1950s. Garner remembered Turing as “funny and witty” and said that he “talked endlessly”.[133]

In 2006, Alan Turing was named with online resources as an LGBT History Month Icon.[134]

Alan Turing memorial statue in Sackville Park, Manchester.

In February 2011, Turing’s papers from the Second World War were bought for the nation with an 11th-hour bid by the National Heritage Memorial Fund, allowing them to stay at Bletchley Park.[135]

The logo of Apple Inc. is often erroneously referred to as a tribute to Alan Turing, with the bite mark a reference to his death.[136] Both the designer of the logo[137] and the company deny that there is any homage to Turing in the designofthelogo.[138][139]StephenFryhasrecountedasking Steve Jobs whether the design was intentional, saying that Jobs’ response was, “God, we wish it were.”[140]

The Turing Rainbow Festival, held in Madurai, India in 2012 for celebrating the LGBT and Genderqueer cause, was named in honour of Alan Turing by Gopi Shankar of Srishti Madurai.[141]

Also in 2012 Turing was inducted into the Legacy Walk, an outdoor public display which celebrates LGBT history and people.[142][143]

The francophone singer-songwriter Salvatore Adamo makes a tribute to Turing with his song “Alan et la Pomme”.[144]

Turing’s life and work featured in a BBC children’s programme about famous scientists – *Absolute Genius with Dick and Dom* – the episode was first broadcast on 12 March 2014.

On 17 May 2014, the world’s first work of public art to recognise Alan Turing as gay was commissioned in Bletchley, close by to Bletchley Park where his wartime work was carried out. The commission was announced by the owners of Milton Keynes-based LGBT venue and nightclub, Pink Punters to mark International Day Against Homophobia and Transphobia. The work was unveiled at a ceremony on Turing’s birthday, 23 June 2014, and is placed outside Pink Punter’s alongside the busy Watling Street, the old main road to London where Turing himself would have passed by on many occasions.

On 22 October 2014, Turing was inducted into the NSA Hall of Honor.[145][146]

1.8.1 Tributes by universities and research institutions

- The computer room at King’s College, Cambridge, Alan Turing’s alma mater, is called the Turing Room.[147]
- The Turing Room at the University of Edinburgh’s School of Informatics houses a bust of Turing by Eduardo Paolozzi, and a set (No. 42/50) of his Turing prints (2000).[148]
- The University of Surrey has a statue of Turing on their main piazza[149] and one of the buildings of

Faculty of Engineering and Physical Sciences is named after him.[150]

- Istanbul Bilgi University organises an annual conference on the theory of computation called "Turing Days".[151]
- The University of Texas at Austin has an honours computer science programme named the Turing Scholars.[152]
- In the early 1960s Stanford University named the sole lecture room of the Polya Hall Mathematics building "Alan Turing Auditorium".[153]
- One of the amphitheatres of the Computer Science department (LIFL[154]) at the University of Lille in Northern France is named in honour of Alan M. Turing (the other amphitheatre is named after Kurt Gödel).

The Alan Turing Building at the University of Manchester

- The Department of Computer Science at Pontifical Catholic University of Chile, the University of Buenos Aires, the Polytechnic University of Puerto Rico, Los Andes University in Bogotá, Colombia, King's College, Cambridge, Bangor University in Wales, the Universities of Ghent and Mons in Belgium, the University of Turin (Università degli Studi di Torino), the University of Puerto Rico at Humacao, Keele University and the University of Washington have computer laboratories named after Turing.
- The University of Manchester, the Open University, Oxford Brookes University and Aarhus University (in Aarhus, Denmark) all have buildings named after Turing.
- Alan Turing Road in the Surrey Research Park[150] and the Alan Turing Way, part of the Manchester inner ring road[155] are named after Alan Turing.
- Carnegie Mellon University has a granite bench, situated in the Hornbostel Mall, with the name "A. M. Turing" carved across the top, "Read" down the left leg, and "Write" down the other.[156]
- The École Internationale des Sciences du Traitement de l'Information has named its third building "Turing".
- The University of Oregon has a bust of Turing on the side of the Deschutes Hall, the computer science building.[157]

1.9. GOVERNMENT APOLOGY AND PARDON

- The École Polytechnique Fédérale de Lausanne has a road and a square named after Alan Turing (Chemin de Alan Turing and Place de Alan Turing).[158]
- The Faculty of Informatics and Information Technologies Slovak University of Technology in Bratislava, Slovakia has a lecture room named "Turing Auditorium".[159]
- The Paris Diderot University has a lecture room named "Amphithéâtre Turing".
- The Paul Sabatier University has a lecture room named "Amphithéâtre Turing" (Bâtiment U4).[160]
- TheDepartmentofComputerScienceattheCollege of Engineering, Guindy has named its lecture hall as the "Turing Hall".
- The Faculty of Mathematics and Computer Science at the University of Würzburg has a lecture hall named "Turing Hörsaal".[161]
- The largest conference hall at the Amsterdam Science Park is named Turingzaal.[162]
- In the summer of 2014, King's College London's School of Natural and Mathematical Sciences awarded the Alan Turing Centenary Prize to "the student ... who has not only achieved outstanding

academic performance, but also made a significant contribution to the life of [the department]".

- The University of Kent will open a brand new college, named Turing College at their Canterbury campus, to provide more than 800 new rooms to accommodate undergraduate and postgraduate students and keep up with increased demand for 'on campus living'. Other features of the new college include a hub to provide a social space for residents, study areas, office space and catering. Scientist George McVittie, an Honorary Professor at Kent from 1972 to 1988, worked with Alan Turing at Bletchley Park.

- The campus of the École polytechnique has a building named after Alan Turing; it is a research centre of which premises are shared by the École Polytechnique, the INRIA and Microsoft.

- The University of Toronto developed the Turing programming language in 1982, named after Alan Turing

- The Faculty of Exact Sciences at the University of BuenosAireshasacomputerlaboratorynamedafter Alan Turing.

1.9 Government apology and pardon

In August 2009, John Graham-Cumming started a petition urging the British Government to apologise for Turing's prosecution as a homosexual.[163][164] The petition received more than 30,000 signatures.[165][166] Prime Minister Gordon Brown acknowledged the petition, releasing a statement on 10 September 2009 apologising and describing the treatment of Turing as "appalling":[165][167]

> Thousands of people have come together to demand justice for Alan Turing and recognition of the appalling way he was treated. While Turing was dealt with under the law of the time and we can't put the clock back, his treatment was of course utterly unfair and I am pleased to have the chance to say how deeply sorry I and we all are for what happened to him ... So on behalf of the British government, and all those who live freely thanks to Alan's work I am very proud to say: we're sorry, you de-served so much better.[165][168]

In December 2011, William Jones created an epetition[169] requesting the British Government pardon Turing for his conviction of "gross indecency":[170]

> We ask the HM Government to grant a pardon to Alan Turing for the conviction of "gross indecency". In 1952, he was convicted of "gross indecency" with another man and was forced to undergo so-called "organo-therapy" – chemical castration. Two years later, he killed himself with cyanide, aged just 41. Alan Turing was driven to a terrible despair and early death by the nation he'd done so much to save. This remains a shame on the British government and British history. A pardon can go to some way to healing this damage. It may act as an apology to many of the other gay men, not as well-known as Alan Turing, who were subjected to these laws.[169]

The petition gathered over 37,000 signatures,[11][169] but the request was discouraged by Lord McNally, who gave the following opinion in his role as the Justice Minister:[171]

> A posthumous pardon was not considered appropriate as Alan Turing was properly convicted of what at the time was a criminal offence. He would have known that his offence was against the law and that he would be prosecuted. It is tragic that Alan Turing was convicted of an offence which now seems both cruel and absurd—particularly poignant given his outstanding contribution to the war effort. However, the law at the time required a prosecution and, as such, long-standing policy has been to accept that such convictions took place and, rather than trying to alter the historical context and to put right what cannot be put right, ensure instead that we never again return to those times.[172]

On 26 July 2012, a bill was introduced in the House of Lords to grant a statutory pardon to Turing for offences under section 11 of the Criminal Law Amendment Act 1885, of which he was convicted on 31 March 1952.[173] Late in the year in a letter to *The Daily Telegraph*, the physicist Stephen Hawking and 10 other signatories including the Astronomer Royal Lord Rees, President of the Royal Society Sir Paul Nurse, Lady Trumpington (who worked for Turing during the war) and Lord Sharkey (the bill's sponsor) called on Prime Minister David Cameron to act on the pardon request.[174] The Government indicated it would support the bill,[175][176][177] and it passed its third reading in the Lords in October.[178]

Before the bill could be debated in the House of Commons,[179] the Government elected to proceed under the royal prerogative of mercy. On 24 December 2013, Queen Elizabeth II signed a pardon[10] for Turing's conviction for gross indecency, with immediate effect. Announcing the pardon, Justice Secretary Chris Grayling said Turing deserved to be "remembered and recognised for his fantastic contribution to the war effort" and not for his later criminal conviction.[9][11] The Queen officially pronounced Turing pardoned in August 2014.[180] TheQueen'sactionisonlythefourthroyalpardongranted since the conclusion of the Second World War.[181] This case is unusual in that pardons are normally granted only when the person is technically innocent, and a request has been made by the family or other interested party. Neither condition was met in regard to Turing's conviction.[182]

In a letter to Prime Minister David Cameron after announcement of the pardon, human rights advocate Peter Tatchell criticised the decision to single out Turing due to his fame and achievements, when thousands of others convicted under the same law have not received pardons.[183] Tatchell also called for a new investigation into Turing's death:

> A new inquiry is long overdue, even if only to dispel any doubts about the true cause of his death – including speculation that he was murdered by the security services (or others). I think murder by state agents is unlikely. There is no known evidence pointing to any such act. However, it is a major failing that this possibility has never been considered or investigated.[184]

1.10 Centenary celebrations

Main article: Alan Turing Year

To mark the 100th anniversary of Turing's birth, the Turing Centenary Advisory Committee (TCAC) coordinated the Alan Turing Year, a year-long programme of events around the world honouring Turing's life and achievements. The TCAC, chaired by S. Barry Cooper with Alan Turing's nephew Sir John Dermot Turing acting as Honorary President, worked with the University of Manchester faculty members and a broad spectrum of people from Cambridge University and Bletchley Park.

David Chalmers on stage for an Alan Turing Year conference at De La Salle University, Manila, 27 March 2012

On 23 June 2012, Google featured an interactive doodle where visitors had to change the instructions of a Turing Machine, so when run, the symbols on the tape would match a provided sequence, featuring "Google" in Baudot-Murray code.[185]

The Bletchley Park Trust collaborated with Winning Moves to publish an Alan Turing edition of the board game Monopoly. The game'ssquaresandcardshavebeen revised to tell the story of Alan Turing's life, from his birthplace in Maida Vale to Hut 8 at Bletchley Park.[186] The game also includes a replica of an original handdrawn board created by William Newman, son of Turing's mentor, Max Newman, which Turing played on in the 1950s.[187]

In the Philippines, the Department of Philosophy at De La Salle University-Manila hosted Turing 2012, an international conference on philosophy, artificial intelligence, and cognitive science from 27 to 28 March 2012 to commemorate the centenary birth of Turing.[188][189] Madurai, India held celebrations, in conjunction with Asia's first Gay Pride festival, with a programme attended by 6,000 students.[190]

1.10.1 UK celebrations

There was a three-day conference in Manchester in June, a two-day conference in San Francisco, organised by the

The London 2012 Olympic Torch flame was passed on in front of Turing's statue in Manchester on his 100th birthday.

ACM, and a birthday party and Turing Centenary Conference in Cambridge organised at King's College, Cambridge and the University of Cambridge, the latter organised by the association Computability in Europe.[191]

The Science Museum in London launched a free exhibition devoted to Turing's life and achievements in June 2012, to run until July 2013.[192] In February 2012, the Royal Mail issued a stamp featuring Turing as part of its "Britons of Distinction" series.[193] The London 2012 Olympic Torch flame was passed on in front of Turing's statue in Sackville Gardens, Manchester, on the evening of 23 June 2012, the 100th anniversary of his birth.

On22June2012ManchesterCityCouncil, inpartnership with the Lesbian and Gay Foundation, launched the Alan Turing Memorial Award which will recognise individuals or groups who have made a significant contribution to the fight against homophobia in Manchester.[194]

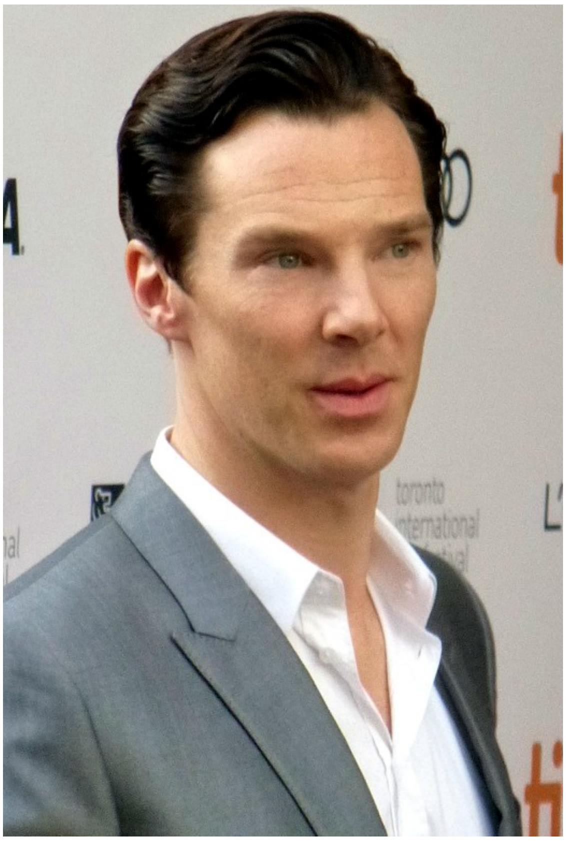
At the University of Oxford, a new course in Computer Science and Philosophy was established to coincide with the centenary of Turing's birth.[195]

Previous events have included a celebration of Turing's life and achievements, at the University of Manchester, arranged by the British Logic Colloquium and the British Society for the History of Mathematics on 5 June 2004.[196]

1.11 Portrayal in adaptations

1.11.1 Theatre

- *Breaking the Code* is a 1986 play by Hugh Whitemore about Alan Turing. The play ran in London's West End beginning in November 1986 and on Broadway from 15 November 1987 to 10 April 1988. There was also a 1996 BBC television production (broadcast in the United States by PBS). In all three performances Turing was played by Derek Jacobi. The Broadway production was nominated for three Tony Awards including Best Actor in a Play, Best Featured Actor in a Play, and Best Direction of a Play, and for two Drama Desk Awards, for Best Actor and Best Featured Actor. Turing was again portrayed by Jacobi in the 1996 television film adaptation of *Breaking the Code*.[197]
- In 2012, in honour of the Turing Centennial, American Lyric Theater commissioned an operatic exploration of the life and death of Alan Turing from composer Justine F. Chen and librettist David Simpatico.[198] Titled *The Life and Death(s) of Alan Turing*, the opera is a historical fantasia on the life of the brilliant scientist. The opera will receive a concert performance in October 2015 in New York City. In November 2014, the opera and several other artistic works inspired by Turing's life were featured on Studio 360.[199]



Benedict Cumberbatch portrayed Turing in the 2014 film The Imitation Game

1.11.2 Literature

- The 2006 novel *A Madman Dreams of Turing Machines* contrasts fictionalised accounts of the lives and ideas of Turing and Kurt Gödel.[200]

1.11.3 Music

- Electronic music duo Matmos released an EP titled *For Alan Turing* in 2006, which was based on material commissioned by Dr. Robert Osserman and David Elsenbud of the Mathematical Sciences Research Institute.[201] In one of its tracks, an original Enigma Machine is sampled.[202]

- In 2012, Spanish group Hidrogenesse dedicated their LP *Un dígito binario dudoso. Recital para Alan Turing* (*A dubious binary digit. Concert for Alan Turing*) to the memory of the mathematician.[203] • A musical work inspired by Turing's life, written by Neil Tennant and Chris Lowe of the Pet Shop Boys, entitled *A Man from the Future*, was announced in late 2013.[204] It was performed by the Pet Shop Boys and Juliet Stevenson (narrator), the BBC Singers, and the BBC Concert Orchestra conducted by Dominic Wheeler at the BBC Proms in the Royal Albert Hall on 23 July 2014.[205]

- *Codebreaker* is also the title of a choral work by the composer James McCarthy. It includes settings of texts by the poets Wilfred Owen, Sara Teasdale, Walt Whitman, Oscar Wilde and Robert Burns that are used to illustrate aspects of Turing's life. It was premiered on 26 April 2014 at the Barbican Centre in London, where it was performed by the Hertfordshire Chorus, who commissioned the work, led by David Temple with the soprano soloist Naomi Harvey providing the voice of Turing's mother.[206][207]

1.11.4 Film

- The drama-documentary *Codebreaker*, about Turing's life, was aired by UK's Channel 4 in November 2011 and was released in the US in October 2012. It is also known as *Britain's Greatest Codebreaker*.

  The film features Ed Stoppard as Turing and Henry Goodman as Franz Greenbaum.[208]

- The historical drama film *The Imitation Game*, directed by Morten Tyldum and starring Benedict Cumberbatch as Turing and Keira Knightley as Joan Clarke, was released in the UK on 14 November 2014 and released theatrically in the US on 28 November 2014. It is about Alan Turing breaking the Enigma code with other codebreakers in Bletchley Park.[209][210][211][212]

1.12 Awards and honours

Turing was elected a Fellow of the Royal Society (FRS) in 1951.[2] In addition, he has had several things named in his honour.

- Good–Turing frequency estimation
- Turing completeness
- Turing degree
- Turing Institute
- Turing Lecture
- Turing machine examples
- Turing patterns
- Turing reduction
- Turing switch
- Unorganised machine

1.13 Notes

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[3] Gray, Paul (29 March 1999). "Alan Turing – Time 100 People of the Century". *Time Magazine*. Providing a blueprint for the electronic digital computer. The fact remains that everyone who taps at a keyboard, opening a spreadsheet or a word-processing program, is working on an incarnation of a Turing machine.

[4] Sipser 2006, p. 137

[5] Beavers 2013, p. 481

[6] See Copeland, Jack (18 June 2012). "Alan Turing: The codebreaker who saved 'millions of lives'". BBC News Technology. Retrieved 26 October 2014. A number of sources state that Winston Churchill said that Turing made the single biggest contribution to Allied victory in the war against Nazi Germany. However both The Churchill Centre and Turing's biographer Andrew Hodges have said they know of no documentary evidence to support this claim nor of the date or context in which Churchill supposedly said it, and the Churchill Centre lists it among their Churchill 'Myths'. See Schilling, Jonathan. "Churchill Said Turing Made the Single Biggest Contribution to Allied Victory". The

Churchill Centre: Myths. Retrieved 9 January 2015. and Hodges, Andrew. “Part 4: The Relay Race”. Update to *Alan Turing: the Enigma*. Retrieved 9 January 2015. A BBC News profile piece that repeated the Churchill claim has subsequently been amended to say there is no evidence for it. See Spencer, Clare (11 September 2009). “Profile: Alan Turing”. BBC News. Update 13 February 2015

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1.13. NOTES

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[25] Hodges 1983, p. 34

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[27] Rachel Hassall, 'The Sherborne Formula: The Making of Alan Turing' 'Vivat!' 2012/13

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[29] Hodges 1983, p. 61

[30] Paul Gray, Alan Turing Time Magazine’s Most Important People of the Century, p.2

[31] Hodges 1983, pp. 82–83

[32] See Section 3 of John Aldrich, “England and Continental Probability in the Inter-War Years”, Journal Electronique d'Histoire des Probabilités et de la Statistique, vol. 5/2 Decembre 2009 Journal Electronique d'Histoire des Probabilités et de la Statistique

[33] Hodges 1983, pp. 88,94

[34] Turing 1937

[35] Church 1936

[36] “von Neumann ... firmly emphasised 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.” Letter by Stanley Frankel to Brian Randell, 1972, quoted in Jack Copeland (2004) *The Essential Turing*, p22.

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[66] Copeland, *The Essential Turing*, pp. 336–337.

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[70] Leavitt 2007, pp. 184–186

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[80] Copeland 2006, p. 72

[81] Gannon 2007, p. 230

[82] Hilton 2006, pp. 197–199

[83] Copeland 2006, pp. 382, 383

[84] Hodges 1983, pp. 245–250

[85] Hodges 1983, p. 273

[86] Hodges 1983, p. 346

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- Alan Turing's publicationScholar, a service provided bys indexed byGoogle Google
- Turing, Alan (October 1950),ery and Intelligence", *Mind* **LIX**"Computing Machin(236): 433–460-, doi:10.1093/mind/LIX.236.433, ISSN 0026-4423, retrieved 2008-08-18
- Oral history interview with Nicholas C. Metropolis, Charles Babbage Institute, University of Min-nesota. Metropolis was the first director of computing services at Los Alamos National

1.16 External links

- Turing family house in Coonoor, India
- A podcast program about Turing made bLab. y Radio
- Alan Turing RKBExplorer
- Alan Turing Year
- CiE 2012: Turing Centenary Conference
- Alan Turincluding a short biographg site maintained byy Andrew Hodges in-
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Chapter 2

Turing machine

This article is about the symbol manipulator. For the deciphering machine, see Bombe. For the test of artificial intelligence, see Turing test. For the instrumental rock band, see Turing Machine (band).

A **Turing machine** is an abstract machine[1] that manipulates symbols on a strip of tape according to a table of rules; to be more exact, it is a mathematical model that defines such a device.[2] Despite the model's simplicity, given any computer algorithm, a Turing machine can be constructed that is capable of simulating that algorithm's logic.[3]

The machine operates on an infinite[4] memory tape divided into *cells*.[5] The machine positions its *head* over a cell and "reads" (scans[6]) the symbol there. Then per the symbol and its present place in a *finite table*[7] of user-specified instructions the machine (i) writes a symbol(e.g. adigitoraletterfromafinitealphabet)inthecell (some models allowing symbol erasure[8] and/or no writing), then (ii) either moves the tape one cell left or right (some models allow no motion, some models move the head),[9] then (iii) (as determined by the observed symbol and the machine's place in the table) either proceeds to a subsequent instruction or halts[10] the computation.

The Turing machine was invented in 1936 by Alan Turing,[11][12] who called it an *a-machine* (automatic machine).[13] With this model Turing was able to answer two questions in the negative: (1) Does a machine exist that can determine whether any arbitrary machine on its tape is "circular" (e.g. freezes, or fails to continue its computational task); similarly, (2) does a machine exist that can determine whether any arbitrary machine on its tape ever prints a given symbol.[14] Thus by providing a mathematical description of a very simple device capable of arbitrary computations, he was able to prove properties of computation in general - and in particular, the uncomputability of the Hilbert Entscheidungsproblem ("decision problem").[15]

Thus, Turing machines prove fundamental limitations on the power of mechanical computation.[16] While they can express arbitrary computations, their minimalistic design makes them unsuitable for computation in practice: actual computers are based on different designs that, unlike Turing machines, use random access memory.

Turing completeness is the ability for a system of instructions to simulate a Turing machine. A programming language that is Turing complete is theoretically capable of expressing all tasks accomplishable by computers; nearly all programming languages are Turing complete.

2.1 Overview

A Turing machine is a general example of a CPU that controls all data manipulation done by a computer, with the canonical machine using sequential memory to store data. More specifically, it is a machine (automaton) capable of enumerating some arbitrary subset of valid strings of an alphabet; these strings are part of a recursively enumerable set.

Assuming a black box, the Turing machine cannot know whether it will eventually enumerate any one specific string of the subset with a given program. This is due to the fact that the halting problem is unsolvable, which has major implications for the theoretical limits of computing.

The Turing machine is capable of processing an unrestricted grammar, which further implies that it is capable of robustly evaluating first-order logic in an infinite number of ways. This is famously demonstrated through lambda calculus.

A Turing machine that is able to simulate any other Turing machine is called a universal Turing machine (**UTM**, or simply a **universal machine**). A more mathematically oriented definition with a similar "universal" nature was introduced by Alonzo Church, whose work on lambda calculus intertwined with Turing's in a formal theory of computation known as the Church–Turing thesis. The thesis states that Turing machines indeed capture the informal notion of effective methods in logic and mathematics, and provide a precise definition of an algorithm or "mechanical procedure". Studying their abstract properties yields many insights into computer science

and complexity theory.

2.1.1 Physical description

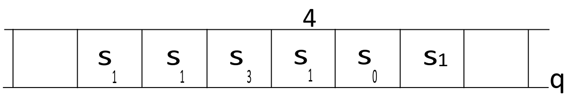
In his 1948 essay, "Intelligent Machinery", Turing wrote that his machine consisted of:

...an unlimited memory capacity obtained in the form of an infinite tape marked out into squares, on each of which a symbol could be printed. At any moment there is one symbol in the machine; it is called the scanned symbol. The machine can alter the scanned symbol, and its behavior is in part determined by that symbol, but the symbols on the tape elsewhere do not affect the behavior of the machine. However, the tape can be moved back and forth through the machine, this being one of the elementary operations of the machine. Any symbol on the tape may therefore eventually have an innings.[17] (Turing 1948, p. 3[18])

2.2 Informal description

For visualizations of Turing machines, see Turing machine gallery.

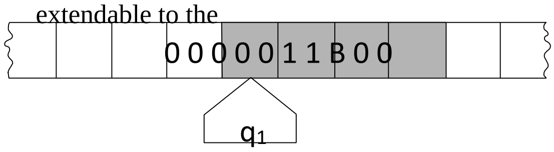
The Turing machine mathematically models a machine that mechanically operates on a tape. On this tape are symbols, which the machine can read and write, one at a time, using a tape head. Operation is fully determined by a finite set of elementary instructions such as "in state 42, if the symbol seen is 0, write a 1; if the symbol seen is 1, change into state 17; in state 17, if the symbol seen is 0, write a 1 and change to state 6;" etc. In the original article ("On computable numbers, with an application to the Entscheidungsproblem", see also references below), Turing imagines not a mechanism, but a person whom he calls the "computer", who executes these deterministic mechanical rules slavishly (or as Turing puts it, "in a desultory manner").



The head is always over a particular square of the tape; only a finite stretch of squares is shown. The instruction to be performed (q_4) is shown over the scanned square. (Drawing after Kleene (1952) p.375.)

More precisely, a Turing machine consists of:

1. A **tape** divided intocells, one nextto the other. Each cell contains a symbol from some finite alphabet. The alphabet contains a special *blank* symbol (here written as '0') and one or more other symbols. The tape is assumed to be arbitrarily extendable to the



Here, the internal state (q_1) is shown inside the head, and the illustration describes the tape as being infinite and pre-filled with "0", the symbol serving as blank. The system's full state (its complete configuration*) consists of the internal state, any non-blank symbols on the tape (in this illustration "11B"), and the position of the head relative to those symbols including blanks, i.e. "011B". (Drawing after Minsky (1967) p. 121).*

left and to the right, i.e., the Turing machine is always supplied with as much tape as it needs for its computation. Cells that have not been written before are assumed to be filled with the blank symbol. In some models the tape has a left end marked with a special symbol; the tape extends or is indefinitely extensible to the right.

2. A **head** that can read and write symbols on the tape and move the tape left and right one (and only one) cell at a time. In some models the head moves and the tape is stationary.

3. A **state register** that stores the state of the Turing machine, one of finitely many. Among these is the special *start state* with which the state register is initialized. These states, writes Turing, replace the "state of mind" a person performing computations would ordinarily be in.

4. A finite **table**[19] of instructions[20] that, given the *state*(q_i) the machine is currently in *and* the *symbol*(a) it is reading on the tape (symbol currently under the head), tells the machine to do the following in sequence (for the 5-tuple models):
   - Either erase or write a symbol (replacing a with a □) *and then*
   - Move the head (which is described by d and can have values: 'L' for one step left *or* 'R' for one step right *or* 'N' for staying in the same place), *and then*
   - Assume the same or a *new state* as prescribed

     (go to state q_i□).

   In the 4-tuple models, erasing or writing a symbol (a □) and moving t specified as separate instructions. Specifically, the table tells the machine to (ia) erase or write a symbol *or* (ib) move the head left or right, *and then* (ii) assume the same or a new state as prescribed, but not both actions (ia) and (ib) in the same instruction. In some models, if there is no entry in the table for the current combination of symbol and state then the machine will halt; other models require all entries to be filled.

Note that every part of the machine (i.e. its state, symbolcollections, and used tape at any given time) and its actions (such as printing, erasing and tape motion) is *finite*, *discrete* and *distinguishable*; it is the unlimited amount of tape and runtime that gives it an unbounded amount of storage space.

2.3 Formal definition

Following Hopcroft and Ullman (1979, p. 148), a (onetape) Turing machine can be formally defined as a 7-tuple $M = \langle Q,\Gamma,b,\Sigma,\delta,q_0,F\rangle$ where

- Q is a finite, non-empty set of *states*
- Γ is a finite, non-empty set of *tape alphabet symbols*
- $b$tooccuronthetapeinfinitelyoftenatanystepduring

  $\in \Gamma$ is the *blank symbol* (the only symbol allowed

  the computation)
- $\Sigma \subseteq \Gamma \setminus \{b\}$ is the set of *input symbols*
- δfunctio: (Qn\calledthe$F$) $\times \Gamma$ *transition functio*$\rightarrow$ $Q \times \Gamma \times \{L,Rn$, whereL isleft} is a partial shift, R is right shift. (A relatively uncommon variant allows "no shift", say N, as a third element of the latter set.) If δ is not defined on the current state and the current tape symbol, then the machine halts.[21]
- $q_0 \in Q$ is the *initial state*
- initial tape contents is said to be$F \subseteq Q$ is the set of

  final or *accepting statesaccepted* by M. Theif it

  eventually halts in a state from F .

Anything that operates according to these specifications is a Turing machine.

The 7-tuple for the 3-state busy beaver looks like this (see more about this busy beaver at Turing machine examples):

- Q = {A,B,C,HALT}
- $\Gamma = \{0,1\}$
- b = 0 ("blank")
- $\Sigma = \{1\}$
- q_0 = A (the initial state)
- F = {HALT}
- δ = see state-table below

Initially all tape cells are marked with 0.

2.4 Additional details required to visualize or implement Turing machines

In the words of van Emde Boas (1990), p. 6: "The set-theoretical object [his formal seven-tuple description similar to the above] provides only partial information on how the machine will behave and what its computations will look like." For instance,

- There will need to be many decisions on what

  thesymbols actually look like, and a failproof way

  of reading and writing symbols indefinitely.
- The shift left and shift right operations may shift

  thetape head across the tape, but when actually

  building a Turing machine it is more practical to

  make the tape slide back and forth under the head

  instead.
- The tape can be finite, and automatically extendedwith blanks as needed (which is closest to the mathematical definition), but it is more common to think of it as stretching infinitely at both ends and being pre-filled with blanks except on the explicitly given finite fragment the tape head is on. (This is, of course, not implementable in practice.) The tape *cannot* be fixed in length, since that would not correspond to the given definition and would seriously limit the range of computations the machine can perform to those of a linear bounded automaton.

2.4.1 Alternative definitions

Definitions in literature sometimes differ slightly, to make arguments or proofs easier or clearer, but this is always done in such a way that the resulting machine has the same computational power. For example, changing the operation") would allow the machine to stay on the sameset $\{L,R\}$ to $\{L,R,N\}$, where N ("None" or "Notape cell instead of moving left or right, does not increase the machine's computational power.

The most common convention represents each "Turing instruction" in a "Turing table" by one of nine 5-tuples, per the convention of Turing/Davis (Turing (1936) in *Undecidable*, p. 126-127 and Davis (2000) p. 152):

(definition 1): **(q_i, S , S /E/N, L/R/N, q)**

(current state **q_i ,** symbol scanned **S ,** print symbol **S** /erase **E**/none **N ,** move_tape_one_square left **L**/right **R**/none **N ,** new state **q)**

Other authors (Minsky (1967) p. 119, Hopcroft and

Ullman (1979) p. 158, Stone (1972) p. 9) adopt a different convention, with new state **q** listed immediately after the scanned symbol S :

(definition 2): **(q_i, S , q , S /E/N, L/R/N)**

(current state **q_i ,** symbol scanned **S ,** new state **q ,** print symbol **S** /erase **E**/none **N ,** move_tape_one_square left **L**/right **R**/none **N)**

For the remainder of this article "definition 1" (the Turing/Davis convention) will be used.

In the following table, Turing's original model allowed only the first three lines that he called N1, N2, N3 (cf Turing in *Undecidable*, p. 126). He allowed for erasure of the "scanned square" by naming a 0th symbol S_0 = "erase" or "blank", etc. However, he did not allow for non-printing, so every instruction-line includes "print symbol S " or "erase" (cf footnote 12 in Post (1947), *Undecidable* p. 300). The abbreviations are Turing's (*Undecidable* p. 119). Subsequent to Turing's original paper in 1936–1937, machine-models have allowed all nine possible types of five-tuples:

Any Turing table (list of instructions) can be constructed from the above nine 5-tuples. For technical reasons, the three non-printing or "N" instructions (4, 5, 6) can usually be dispensed with. For examples see Turing machine examples.

Less frequently the use of 4-tuples are encountered: these represent a further atomization of the Turing instructions (cf Post (1947), Boolos & Jeffrey (1974, 1999), DavisSigal-Weyuker(1994)); alsoseemoreatPost–Turingmachine.

2.4.2 The "state"

The word "state" used in context of Turing machines can be a source of confusion, as it can mean two things. Most commentators after Turing have used "state" to mean the name/designator of the current instruction to be performed—i.e. the contents of the state register. But Turing (1936) made a strong distinction between a record of what he called the machine's "m-configuration", (its internal state) and the machine's (or person's) "state of progress" through the computation - the current state of the total system. What Turing called "the state formula" includes both the current instruction and *all* the symbols on the tape:

> Thus the state of progress of the computation at any stage is completely determined by the note of instructions and the symbols on the tape. That is, the **state of the system** may be described by a single expression (sequence of symbols) consisting of the symbols on the tape followed by Δ (which we suppose not to appear elsewhere) and then by the note of instructions. This expression is called the 'state formula'.
>
> — *Undecidable*, p.139–140, emphasis added

Earlier in his paper Turing carried this even further: he gives an example where he placed a symbol of the current "m-configuration"—the instruction's label—beneath the scanned square, together with all the symbols on the tape (*Undecidable*, p. 121); this he calls "the *complete configuration*" (*Undecidable*, p. 118). To print the "complete configuration" on one line, he places the state-label/mconfiguration to the *left* of the scanned symbol.

A variant of this is seen in Kleene (1952) where Kleene shows how to write the Gödel number of a machine's "situation": he places the "m-configuration" symbol q_4 over the scanned square in roughly the center of the 6 non-blank squares on the tape (see the Turing-tape figure in this article) and puts it to the *right* of the scanned square. But Kleene refers to "q_4" itself as "the machine state" (Kleene, p. 374-375). Hopcroft and Ullman call this composite the "instantaneous description" and follow the Turing convention of putting the "current state" (instruction-label, m-configuration) to the *left* of the scanned symbol (p. 149).

Example: total state of 3-state 2-symbol busy beaver after 3 "moves" (taken from example "run" in the figure below):

1**A**1

This means: after three moves the tape has ... 000110000 ... on it, the head is scanning the right-most 1, and the state is **A**. Blanks (in this case represented by "0"s) can be part of the total state as shown here: **B**01; the tape has a single 1 on it, but the head is scanning the 0 ("blank") to its left and the state is **B**.

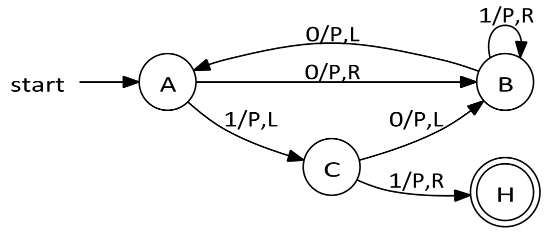
"State" in the context of Turing machines should be clarified as to which is being described: (*i*) the current instruction, or (*ii*) the list of symbols on the tape together with the current instruction, or (*iii*) the list of symbols on the tape together with the current instruction placed to the left of the scanned symbol or to the right of the scanned symbol.

Turing's biographer Andrew Hodges (1983: 107) has noted and discussed this confusion.

2.4.3 Turing machine "state" diagrams

To the right: the above TABLE as expressed as a "state transition" diagram.

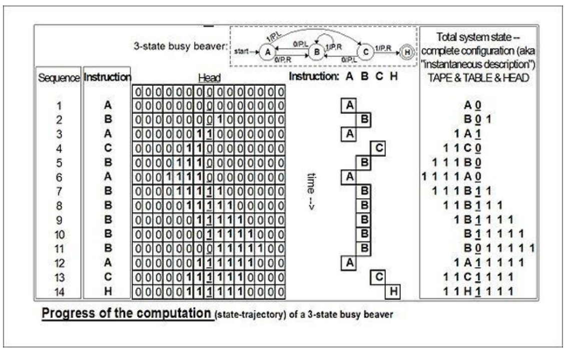
Usually large TABLES are better left as tables (Booth, p. 74). They are more readily simulated by computer in tab-



The "3-state busy beaver" Turing machine in a finite state representation. Each circle represents a "state" of the TABLE—an "m-configuration" or "instruction". "Direction" of a state transition *is shown by an arrow. The label (e.g.. **0/P,R**) near the outgoing state (at the "tail" of the arrow) specifies the scanned symbol that causes a particular transition (e.g. **0**) followed by a slash /, followed by the subsequent "behaviors" of the machine, e.g. "**P** Print" then move tape "**R** Right". No general accepted format exists. The convention shown is after McClusky (1965), Booth (1967), Hill, and Peterson (1974).*

ular form (Booth, p. 74). However, certain concepts—e.g. machines with "reset" states and machines with repeating patterns (cf Hill and Peterson p. 244ff)—can be more readily seen when viewed as a drawing.

Whether a drawing represents an improvement on its TABLE must be decided by the reader for the particular context. See Finite state machine for more.



The evolution of the busy-beaver's computation starts at the top and proceeds to the bottom.

The reader should again be cautioned that such diagrams represent a snapshot of their TABLE frozen in time, *not* the course ("trajectory") of a computation *through* time and/or space. While every time the busy beaver machine "runs" it will always follow the same state-trajectory, this is not true for the "copy" machine that can be provided with variable input "parameters".

The diagram "Progress of the computation" shows the 3state busy beaver's "state" (instruction) progress through its computation from start to finish. On the far right is the Turing "complete configuration" (Kleene "situation", Hopcroft–Ullman "instantaneous description") at each step. If the machine were to be stopped and cleared to blank both the "state register" and entire tape, these "configurations" could be used to rekindle a computation anywhere in its progress (cf Turing (1936) *Undecidable* pp. 139–140).

2.5 Models equivalent to the Turing machine model

See also: Turing machine equivalents, Register machine and Post–Turing machine

Many machines that might be thought to have more computational capability than a simple universal Turing machine can be shown to have no more power (Hopcroft and Ullman p. 159, cf Minsky (1967)). They might compute faster, perhaps, or use less memory, or their instruction set might be smaller, but they cannot compute more powerfully (i.e. more mathematical functions). (Recall that the Church–Turing thesis *hypothesizes* this to be true for any kind of machine: that anything that can be "computed" can be computed by some Turing machine.)

A Turing machine is equivalent to a pushdown automaton that has been made more flexible and concise by relaxing the last-in-first-out requirement of its stack.

Attheotherextreme, someverysimplemodelsturnoutto be Turing-equivalent, i.e. to have the same computational power as the Turing machine model.

Common equivalent models are the multi-tape Turing machine, multi-track Turing machine, machines with input and output, and the *non-deterministic* Turing machine (NDTM) as opposed to the *deterministic* Turing machine (DTM) for which the action table has at most one entry for each combination of symbol and state.

Read-only, right-moving Turing machines are equivalent to NDFAs (as well as DFAs by conversion using the NDFA to DFA conversion algorithm).

For practical and didactical intentions the equivalent register machine can be used as a usual assembly programming language.

2.6 Choice c-machines, Oracle omachines

Early in his paper (1936) Turing makes a distinction between an “automatic machine”—its “motion ... completely determined by the configuration” and a “choice machine":

> ...whose motion is only partially determined by the configuration ... When such a machine reaches one of these ambiguous configurations, it cannot go on until some arbitrary choice has been made by an external operator. This would be the case if we were using machines to deal with axiomatic systems.

2.8. COMPARISON WITH REAL MACHINES

> — *Undecidable*, p. 118

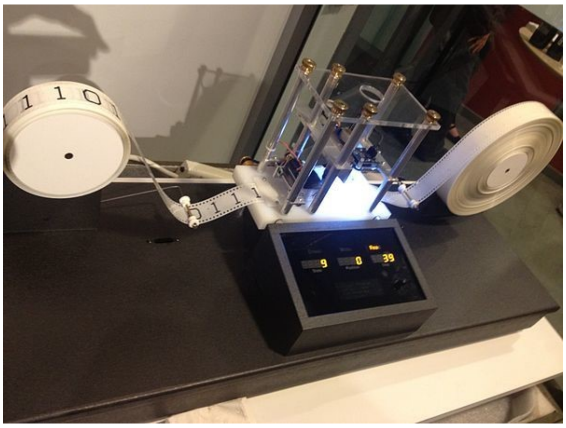
Turing (1936) does not elaborate further except in a footnote in which he describes how to use an a-machine to “find all the provable formulae of the [Hilbert] calculus” rather than use a choice machine. He “suppose[s] that the choices are always between two possibilities 0 and 1. Each proof will then be determined by a sequence of choices $i_1, i_2, ..., i$ ($i_1 = 0$ or 1, $i_2 = 0$ or 1, ..., $i = 0$ or 1), and hence the number $2^n + i_1 2^{n-1} + i_2 2^{n-2} + ... + i$ completely determines the proof. The automatic machine carries out successively proof 1, proof 2, proof 3, ...” (Footnote ‡, *Undecidable*, p. 138)

This is indeed the technique by which a deterministic (i.e. a-) Turing machine can be used to mimic the action of a nondeterministic Turing machine; Turing solved the matter in a footnote and appears to dismiss it from further consideration.

An oracle machine or o-machine is a Turing a-machine that pauses its computation at state "**o**" while, to complete its calculation, it “awaits the decision” of “the oracle”— an unspecified entity “apart from saying that it cannot be a machine” (Turing (1939), Undecidable p. 166–168). The concept is now actively used by mathematicians.

2.7 Universal Turing machines

Main article: Universal Turing machine As Turing wrote in *Undecidable*, p. 128 (italics added):



An implementation of a Turing machine

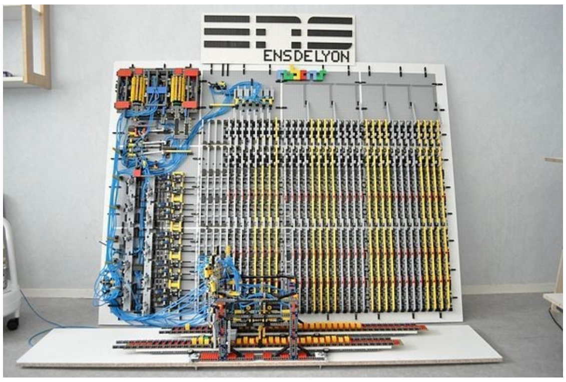
> It is possible to invent a *single machine* which can be used to compute *any* computable sequence. If this machine **U** is supplied with the tape on the beginning of which is written the string of quintuples separated by semicolons of some computing machine **M**, then **U** will compute the same sequence as **M**.

This finding is now taken for granted, but at the time (1936) it was considered astonishing. The model of computation that Turing called his “universal machine”—"**U**" for short—is considered by some (cf Davis (2000)) to have been the fundamental theoretical breakthrough that led to the notion of the stored-program computer.

> Turing’s paper ... contains, in essence, the invention of the modern computer and some of the programming techniques that accompanied it.
> — Minsky (1967), p. 104

In terms of computational complexity, a multi-tape universal Turing machine need only be slower by logarithmic factor compared to the machines it simulates. This result was obtained in 1966 by F. C. Hennie and R. E. Stearns. (Arora and Barak, 2009, theorem 1.9)

2.8 Comparison with real machines



A Turing machine realisation in LEGO

It is often said that Turing machines, unlike simpler automata, are as powerful as real machines, and are able to execute any operation that a real program can. What is neglected in this statement is that, because a real machine can only have a finite number of *configurations*, this "real machine" is really nothing but a linear bounded automaton. On the otherhand, Turing machinesare equivalent to machines that have an unlimited amount of storage space for their computations. However, Turing machines are not intended to model computers, but rather they are intended to model computation itself. Historically, computers, which compute only on their (fixed) internal storage, were developed only later.

There are a number of ways to explain why Turing machines are useful models of real computers:

1. Anything a real computer can compute, a Turing machine can also compute. For example: "A Turing machine can simulate any type of subroutine found in programming languages, including recursive procedures and any of the known parameter-passing mechanisms" (Hopcroft and Ullman p. 157). A large enough FSA can also model any real computer, disregarding IO. Thus, a statement about the limitations of Turing machines will also apply to real computers.

2. The difference lies only with the ability of a Turing machine to manipulate an unbounded amount of data. However, given a finite amount of time, a Turing machine (like a real machine) can only manipulate a finite amount of data.

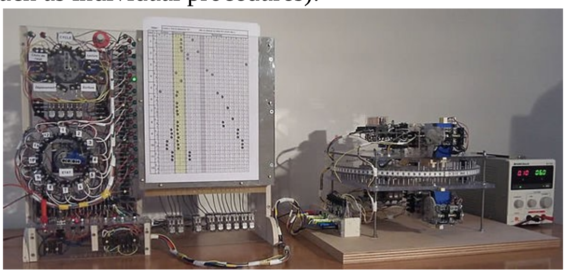
3. Like a Turing machine, a real machine can have its storage space enlarged as needed, by acquiring more disks or other storage media. If the supply of these runs short, the Turing machine may become less useful as a model. But the fact is that neither Turing machines nor real machines need astronomical amounts of storage space in order to perform useful computation. The processing time required is usually much more of a problem.

4. Descriptions of real machine programs using simpler abstract models are often much more complex than descriptions using Turing machines. For example, a Turing machine describing an algorithm may have a few hundred states, while the equivalent deterministic finite automaton (DFA) on a given real machine has quadrillions. This makes the DFA representation infeasible to analyze.

5. Turing machines describe algorithms independent of how much memory they use. There is a limit to the memory possessed by any current machine, but this limit can rise arbitrarily in time. Turing machines allow us to make statements about algorithms which will (theoretically) hold forever, regardless of advances in *conventional* computing machine architecture.

6. Turing machines simplify the statement of algorithms. Algorithms running on Turing-equivalent abstract machines are usually more general than their counterparts running on real machines, because they have arbitrary-precision data types available and never have to deal with unexpected conditions (including, but not limited to, running out of memory).

One way in which Turing machines are a poor model for programs is that many real programs, such as operating systems and word processors, are written to receive unbounded input over time, and therefore do not halt. Turing machines do not model such ongoing computation well (but can still model portions of it, such as individual procedures).



An experimental prototype to achieve Turing machine

2.8.1 Limitations of Turing machines

Computational complexity theory

Further information: Computational complexity theory

A limitation of Turing machines is that they do not model the strengths of a particular arrangement well. For instance, modern stored-program computers are actually instances of a more specific form of abstract machine known as the random access stored program machine or RASP machine model. Like the Universal Turing machine the RASP stores its "program" in "memory" external to its finite-state machine's "instructions". Unlike the universal Turing machine, the RASP has an infinite number of distinguishable, numbered but unbounded "registers"—memory "cells" that can contain any integer (cf. Elgot and Robinson (1964), Hartmanis (1971), and in particular Cook-Rechow (1973); references at random access machine). The RASP's finite-state machine is equipped with the capability for indirect addressing (e.g. the contents of one register can be used as an address to specify another register); thus the RASP's "program" can address any register in the register-sequence. The upshot of this distinction is that there are computational optimizations that can be performed based on the memory indices, which are not possible in a general Turing machine; thus when Turing machines are used as the basis for bounding running times, a 'false lower bound' can be proven on certain algorithms' running times (due to the false simplifying assumption of a Turing machine). An example of this is binary search, an algorithm that can be shown to perform more quickly when using the RASP model of computation rather than the Turing machine model.

Concurrency

Another limitation of Turing machines is that they do not model concurrency well. For example, there is a bound on the size of integer that can be computed by an alwayshalting nondeterministic Turing machine starting on a blank tape. (See article on unbounded nondeterminism.) By contrast, there are always-halting concurrent systems with no inputs that can compute an integer of unbounded

size. (A process can be created with local storage that is initialized with a count of 0 that concurrently sends itself both a stop and a go message. When it receives a go message, it increments its count by 1 and sends itself a go message. When it receives a stop message, it stops with an unbounded number in its local storage.)

2.9 History

See also: Algorithm and Church–Turing thesis

They were described in 1936 by Alan Turing.

2.9.1 Historical background: computational machinery

Robin Gandy (1919–1995)—a student of Alan Turing (1912–1954) and his lifelong friend—traces the lineage of the notion of "calculating machine" back to Babbage (circa 1834) and actually proposes "Babbage's Thesis":

> *That the whole of development and operations of analysis are now capable of being executed by machinery*. — (italics in Babbage as cited by Gandy, p. 54)

Gandy's analysis of Babbage's Analytical Engine describes the following five operations (cf p. 52–53):

1. The arithmetic functions +, −, × where − indicates "proper" subtraction x − y = 0 if y ≥ x
2. Any sequence of operations is an operation
3. Iteration of an operation (repeating n times an operation P)
4. Conditional iteration (repeating n times an operation P conditional on the "success" of test T)
5. Conditional transfer (i.e. conditional "goto").

Gandy states that "the functions which can be calculated by (1), (2), and (4) are precisely those which are Turing computable." (p. 53). He cites other proposals for "universal calculating machines" including those of Percy Ludgate (1909), Leonardo Torres y Quevedo (1914), Maurice d'Ocagne (1922), Louis Couffignal (1933), Vannevar Bush (1936), Howard Aiken (1937). However:

> ... the emphasis is on programming a fixed iterable sequence of arithmetical operations. The fundamental importance of conditional iteration and conditional transfer for a general theory of calculating machines is not recognized ...
> — Gandy p. 55

2.9.2 The Entscheidungsproblem (the "decision problem"): Hilbert's tenth question of 1900

With regards to Hilbert's problems posed by the famous mathematician David Hilbert in 1900, an aspect of problem #10 had been floating about for almost 30 years before it was framed precisely. Hilbert's original expression for #10 is as follows:

> **10. Determination of the solvability of a Diophantine equation**. Given a Diophantine equation with any number of unknown quantities and with rational integral coefficients: To devise a process according to which it can be determined in a finite number of operations whether the equation is solvable in rational integers.
>
> The Entscheidungsproblem [decision problem for first-order logic] is solved when

> we know a procedure that allows for any given logical expression to decide by finitely many operations its validity or satisfiability ... The Entscheidungsproblem must be considered the main problem of mathematical logic.
>
> — quoted, with this translation and the original German, in Dershowitz and Gurevich, 2008

By 1922, this notion of "Entscheidungsproblem" had developed a bit, and H. Behmann stated that

> ... most general form of the Entscheidungsproblem [is] as follows:
>
> > A quite definite generally applicable prescription is required which will allow one to decide in a finite number of steps the truth or falsity of a given purely logical assertion
> > ...
> > — Gandy p. 57, quoting Behmann

> Behmann remarks that ... the general problem is equivalent to the problem of deciding which mathematical propositions are true. — *ibid.*
>
> If one were able to solve the Entscheidungsproblem then one would have a "procedure for solving many (or even all) mathematical problems".
>
> — *ibid.*, p. 92

By the 1928 international congress of mathematicians, Hilbert "made his questions quite precise. First, was mathematics *complete* ... Second, was mathematics *consistent* ... And thirdly, was mathematics *decidable*?" (Hodges p. 91, Hawking p. 1121). The first two questions were answered in 1930 by Kurt Gödel at the very same meeting where Hilbert delivered his retirement speech (much to the chagrin of Hilbert); the third—the Entscheidungsproblem—had to wait until the mid-1930s.

The problem was that an answer first required a precise definition of "*definite general applicable prescription*", which Princeton professor Alonzo Church would come to call "effective calculability", and in 1928 no such definition existed. But over the next 6–7 years Emil Post developed his definition of a worker moving from room to room writing and erasing marks per a list of instructions (Post 1936), as did Church and his two students Stephen Kleene and J. B. Rosser by use of Church's lambda-calculus and Gödel's recursion theory (1934). Church's paper (published 15 April 1936) showed that the Entscheidungsproblem was indeed "undecidable" and beat Turing to the punch by almost a year (Turing's paper submitted 28 May 1936, published January 1937). In the meantime, Emil Post submitted a brief paper in the fall of 1936, so Turing at least had priority over Post. While Church refereed Turing's paper, Turing had time to study Church's paper and add an Appendix where he sketched a proof that Church's lambda-calculus and his machines would compute the same functions.

> But what Church had done was something rather different, and in a certain sense weaker. ... the Turing construction was more direct, and provided an argument from first principles, closing the gap in Church's demonstration.
>
> — Hodges p. 112

And Post had only proposed a definition of calculability and criticized Church's "definition", but had proved nothing.

2.9.3 Alan Turing's a-(automatic)machine

In the spring of 1935, Turing as a young Master's student at King's College Cambridge, UK, took on the challenge; he had been stimulated by the lectures of the logician M. H. A. Newman "and learned from them of Gödel's work and the Entscheidungsproblem ... Newman used the word 'mechanical' ... In his obituary of Turing 1955 Newman writes:

> To the question 'what is a "mechanical" process?' Turing returned the characteristic answer 'Something that can be done by a machine' and he embarked on the highly congenial task of analysing the general notion of a computing machine. — Gandy, p. 74

Gandy states that:

> I suppose, but do not know, that Turing, right from the start of his work, had as his goal a proof of the undecidability of the Entscheidungsproblem. He told me that the 'main idea' of the paper came to him when he was lying in Grantchester meadows in the summer of 1935. The 'main idea' might have either been his analysis of computation or his realization that there was a universal machine, and so a diagonal argument to prove unsolvability.
>
> — *ibid.*, p. 76

While Gandy believed that Newman's statement above is "misleading", this opinion is not shared by all. Turing had a lifelong interest in machines: "Alan had dreamt of inventing typewriters as a boy; [his mother] Mrs. Turing had a typewriter; and he could well have begun by asking himself what was meant by calling a typewriter 'mechanical'" (Hodges p. 96). While at Princeton pursuing his PhD, Turing built a Boolean-logic multiplier (see below). His PhD thesis, titled "Systems of Logic Based on Ordinals", contains the following definition of "a computable function":

> It was stated above that 'a function is effectively calculable if its values can be found by some purely mechanical process'. We may take this statement literally, understanding by a purely mechanical process one which could be carried out by a machine. It is possible to give a mathematical description, in a certain normal form, of the structures of these machines. The development of these ideas leads to the author's definition of a computable function, and to an identification of computability with effective calculability. It is not difficult, though somewhat laborious, to prove that these three definitions [the 3rd is the λ-calculus] are equivalent.
> — Turing (1939) in *The Undecidable*, p. 160

2.10. SEE ALSO

When Turing returned to the UK he ultimately became jointly responsible for breaking the German secret codes created by encryption machines called "The Enigma"; he also became involved in the design of the ACE (Automatic Computing Engine), "[Turing's] ACE proposal was effectively self-contained, and its roots lay not in the EDVAC [the USA's initiative], but in his own universal machine" (Hodges p. 318). Arguments still continue concerning the origin and nature of what has been named by Kleene (1952) Turing's Thesis. But what Turing *did prove* with his computational-machine model appears in his paper *On Computable Numbers, With an Application to the Entscheidungsproblem* (1937):

> [that] the Hilbert Entscheidungsproblem can have no solution ... I propose, therefore to show that there can be no general process for determining whether a given formula U of the functional calculus K is provable, i.e. that there can be no machine which, supplied with any one U of these formulae, will eventually say whether U is provable. — from Turing's paper as reprinted in *The Undecidable*, p. 145

Turing's example (his second proof): If one is to ask for a general procedure to tell us: "Does this machine ever print 0", the question is "undecidable".

2.9.4 1937–1970: The "digital computer", the birth of "computer science"

In 1937, while at Princeton working on his PhD thesis, Turing built a digital (Boolean-logic) multiplier from scratch, making his own electromechanical relays (Hodges p. 138). "Alan's task was to embody the logical design of a Turing machine in a network of relayoperated switches ..." (Hodges p. 138). While Turing might have been just initially curious and experimenting, quite-earnest work in the same direction was going in Germany (Konrad Zuse (1938)), and in the United States (Howard Aiken) and George Stibitz (1937); the fruits of their labors were used by the Axis and Allied military in World War II (cf Hodges p. 298–299). In the early to mid-1950s Hao Wang and Marvin Minsky reduced the Turing machine to a simpler form (a precursor to the Post-Turing machine of Martin Davis); simultaneously European researchers were reducing the newfangled electronic computer to a computer-like theoretical object equivalent to what was now being called a "Turing machine". In the late 1950s and early 1960s, the coincidentally parallel developments of Melzak and Lambek (1961), Minsky (1961), and Shepherdson and Sturgis (1961) carried the European work further and reduced the Turing machine to a more friendly, computerlike abstract model called the counter machine; Elgot and Robinson (1964), Hartmanis (1971), Cook and Reckhow (1973) carried this work even further with the register machine and random access machine models—but basically all are just multi-tape Turing machines with an arithmetic-like instruction set.

2.9.5 1970–present: the Turing machine as a model of computation

Today, the counter, register and random-access machines and their sire the Turing machine continue to be the models of choice for theorists investigating questions in the theory of computation. In particular, computational complexity theory makes use of the Turing machine:

> Depending on the objects one likes to manipulate in the computations (numbers like nonnegative integers or alphanumeric strings), two models have obtained a dominant position in machine-based complexity theory:
>
> > *the off-line multitape Turing machine*..., which represents the standard model for string-oriented computation, and the *random*

> *access machine (RAM)* as introduced by Cook and Reckhow ..., which models the idealized Von Neumann style computer.
> — van Emde Boas 1990:4

> Only in the related area of analysis of algorithms this role is taken over by the RAM model.
> — van Emde Boas 1990:16

Kantorovitz(2005) Sweden was the first to show the most simple obvious representation of Turing Machines published academically which unifies Turing Machines with mathematical analysis and analog computers.

2.10 See also

2.11 Notes

[1] Minsky 1967:107 "In his 1936 paper, A. M. Turing defined the class of abstract machines that now bear his name. A Turing machine is a finite-state machine associated with a special kind of environment -- its tape -- in which it can store (and later recover) sequences of symbols", also Stone 1972:8 where the word "machine" is in quotation marks.

[2] Stone 1972:8 states "This "machine" is an abstract mathematical model", also cf Sipser 2006:137ff that describes the "Turing machine model". Rogers 1987 (1967):13 refers to "Turing's characterization", Boolos Burgess and Jeffrey 2002:25 refers to a "specific kind of idealized machine".

[3] Sipser 2006:137 "A Turing machine can do everything that a real computer can do".

[4] cf Sipser 2002:137. Also Rogers 1987 (1967):13 describes "a paper tape of infinite length in both directions". Minsky 1967:118 states "The tape is regarded as infinite in both directions". Boolos Burgess and Jeffrey 2002:25 include the possibility of "there is someone stationed at each end to add extra blank squares as needed".

[5] cf Rogers 1987 (1967):13. Other authors use the word "square" e.g. Boolos Burgess Jeffrey 2002:35, Minsky 1967:117, Penrose 1989:37.

[6] The word used by e.g. Davis 2000:151

[7] This table represents an algorithm or "effective computational procedure" which is necessarily finite; see Penrose 1989:30ff, Stone 1972:3ff.

[8] Boolos Burgess and Jeffrey 2002:25

[9] Boolos Burgess Jeffry 2002:25 illustrate the machine as moving along the tape. Penrose 1989:36-37 describes himself as "uncomfortable" with an infinite tape observing that it "might be hard to shift!"; he "prefer[s] to think of the tape as representing some external environment through which our finite device can move" and after observing that the " 'movement' is a convenient way of picturing things" and then suggests that "the device receives all its input from this environment.

[10] "Also by convention one of the states is distinguished as the stopping state and is given the name HALT" (Stone 1972:9). Turing's original description did not include a HALT instruction but he did allow for a "circular" condition, a "configuration from which there is no possible move" (see Turing 1936 in *The Undecidable* 1967:119); this notion was added in the 1950s; see more at Halting problem.

[11] Andrew Hodges (2012). *Alan Turing: The Enigma (THE CENTENARY EDITION)*. Princeton University Press. ISBN 978-0-691-15564-7.

[12] The idea came to him in mid-1935 (perhaps, see more in the History section) after a question posed by M. H. A. Newman in his lectures: "Was there a definite method, or as Newman put it, a *mechanical process* which could be applied to a mathematical statement, and which would come up with the answer as to whether it was provable" (Hodges 1983:93). Turing submitted his paper on 31 May 1936 to the London Mathematical Society for its *Proceedings* (cf Hodges 1983:112), but it was *published* in early 1937 and offprints were available in February 1937 (cf Hodges 1983:129).

[13] See footnote in Davis 2000:151.

[14] Turing 1936 in *The Undecidable* 1965:132-134; Turing's definition of "circular" is found on page 119.

[15] Turing 1936 in *The Undecidable* 1965:145

[16] Sipser 2006:137 observes that "A Turing machine can do everything that a real computer can do. Nevertheless, even a Turing machine cannot solve certain problems. In a very real sense, these problems are beyond the theoretical limits of computation."

[17] See the definition of "innings" on Wiktionary

[18] A.M. Turing (1948). "Intelligent Machinery (manuscript)". The Turing Archive. p. 3.

[19] Occasionally called an **action table** or **transition function**

[20] Usually quintuples [5-tuples]: $q_i a \rightarrow q_i$□a□d , but sometimes quadruples [4-tuples].

[21] p.149; in particular, Hopcroft and Ullman assume that δ is undefined on all states from F

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- to understand life mechanisms with a DNA-

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  Biology, processor.
- The Turing machinmachine, its functionality and historical factse—Summary about the Turing
- The Wolfram 2,3 Turing Machine Research PrizStephen Wolfram's $25,000 prize for the proof ore— disproof of the universality of the potentially smallest universal Turing Machine. The contest has ended, with the proof affirming the machine's universality.
- leny,"Turing Machine Causal NetworkWolfram Demonstrations Projecs" by Enrique Ze-t.
- Turing Machines at DMOZ
- Purely mechanical Turing Machine
- JSTMSimulatosimulator, written in JavaScript. (r: an open source Turing Machinesource code on

  GitHub)

Chapter 3

Bletchley Park

Bletchley
Park

Location in England

Bletchley Park was the central site for Britain's codebreakers during World War Two. Run by the Government Code and Cypher School (GC&CS), it regularly penetrated the secret communications of the Axis Powers – most importantly the German Enigma and Lorenz ciphers. The official historian of World War II British Intelligence has written that the "Ultra" intelligence produced at Bletchley shortened the war by two to four years, and that without it the outcome of the war would have been uncertain.[1]

Located in Milton Keynes, Buckinghamshire, England, Bletchley Park is now a flourishing heritage attraction. Open seven days a week, it is popular with individuals and families as well as school groups and tour parties.

The stableyard cottages

3.1 Site

Bletchley Park is opposite Bletchley railway station. It is close to junctions 13 and 14 of the M1. Located 50 miles (80 km) northwest of London, the site appears in the Domesday Book as part of the Manor of Eaton. Browne Willis built a mansion there in 1711, but after Thomas Harrison purchased the property in 1793 this was pulled down. It was first known as Bletchley Park after its purchase by Samuel Lipscomb Seckham in 1877.[2] The estate of 581 acres (235 ha) was bought in 1883 by Sir Herbert Samuel Leon, who expanded the then-existing farmhouse[3] into the present "maudlin and monstrous pile"[4] combining Victorian Gothic, Tudor, and Dutch Baroque styles.

In 1938, the mansion and much of the site was bought by a builder planning a housing estate, but in May 1938 Admiral Sir Hugh Sinclair, head of the Secret Intelligence Service(SISorMI6)boughtthemansionand58acres(23 ha) for use by GC&CS and SIS in the event of war.[5]

A key advantage seen by Sinclair and his colleagues (inspecting the site under the cover of "Captain Ridley's shooting party")[6] was Bletchley's geographical centrality. It was almost immediately adjacent to Bletchley railway station, where the "Varsity Line" between Oxford and Cambridge – whose universities were expected to supply many of the code-breakers – met the main West Coast railway line connecting London, Birmingham,

Manchester, Liverpool, Glasgow and Edinburgh. Watling Street, the main road linking London to the north-west (now the A5) was close by, and high-volume communication links were available at the telegraph and telephone repeater station in nearby Fenny Stratford.

Bletchley Park was known as "B.P." to those who worked there.[7] "Station X" (X = Roman numeral ten), "London Signals Intelligence Centre", and "Government Communications Headquarters" were all cover names used during the war.[8] (The formal posting of the many "Wrens" – members of the Women's Royal Naval Service – working there was to HMS Pembroke V.)

3.2 Personnel

Stephen Kettle's 2007 statue of Alan Turing

Commander Alastair Denniston was operational head of GC&CS from 1919 to 1942, beginning with its formation from the Admiralty's Room 40 (NID25) and the War Office's MI1b.[9] Key GC&CS cryptanalysts who moved from London to Bletchley Park included John Tiltman, Dillwyn "Dilly" Knox, Josh Cooper, and Nigel de Grey. These people had a variety of backgrounds – linguists, chess champions, and crossword experts were common, and in Knox's case papyrology. The British War Office recruited top solvers of cryptic crossword puzzles, as these individuals had strong lateral thinking skills.[10]

On the day Britain declared war on Germany, Denniston wrote to the Foreign Office about recruiting "men of the professor type".[11] Personal networking drove early recruitments, particularly of men from the universities of Cambridge and Oxford. Trustworthy women were similarly recruited for administrative and clerical jobs.[12] In one 1941 recruiting stratagem *The Daily Telegraph* was asked to organise a crossword competition, after which promising contestants were discreetly approached about "a particular type of work as a contribution to the war effort".[13]

Denniston recognised, however, that the enemy's use of electromech anical cipher machines meant that formally trained mathematicians would be needed as well;[14] Oxford's Peter Twinn joined GC&CS in February 1939;[15] Cambridge's Alan Turing[16] and Gordon Welchman[17] began training in 1938 and reported to Bletchley the day after war was declared, along with John Jeffreys. Later-recruited cryptanalysts included the mathematicians Derek Taunt,[18] Jack Good,[19] Bill Tutte,[20] and Max Newman; historian Harry Hinsley, and chess champions Hugh Alexander and Stuart Milner-Barry.[21] Joan Clarke (eventually deputy head of Hut 8) was one of the few women employed at Bletchley as a full-fledged cryptanalyst.[22][23]

This eclectic staff of "Boffins and Debs"[24] caused GC&CS to be whimsically dubbed the "Golf, Cheese and Chess Society",[25] with the female staff in Dilwyn Knox's section sometimes termed "Dilly's Fillies".[26] During a September 1941 morale-boosting visit, Winston Churchill reportedly remarked to Denniston: "I told you to leave no stone unturned to get staff, but I had no idea you had taken me so literally."[27] Six weeks later, having failed to get sufficient typing and unskilled staff to achieve the productivity that was possible, Turing, Welchman, Alexander and Milner-Barry wrote directly to Churchill. His response was "Action this day make sure they have all they want on extreme priority and report to me that this has been done."[28]

After initial training at the Inter-Service Special Intelligence School set up by John Tiltman (initially at an RAF depot in Buckingham and later in Bedford – where it was known locally as "the Spy School")[29] staff worked a sixday week, rotating through three shifts: 4 p.m. to midnight, midnight to 8 a.m. (the most disliked shift), and 8 a.m. to 4 p.m., each with a half-hour meal break. At the end of the third week a worker went off at 8 a.m. and came back at 4 p.m., thus putting in sixteen hours on that last day. The irregular hours affected workers' health and social life, as well as the routines of the nearby homes at which most staff lodged. The work was tedious and demanded intense concentration; staff got one week's leave four times a year, but some "girls" collapsed and required extended rest.[30] A small number of men (e.g. Post Office experts in Morse code or German) worked part-time.

In January 1945, at the peak of codebreaking efforts, some 9,000 personnel were working at Bletchley;[31] over 12,000 different persons (some 80% of them women, primarily seconded from Britain's armed forces and Civil Service[32]) were assigned there at various points throughout the war.

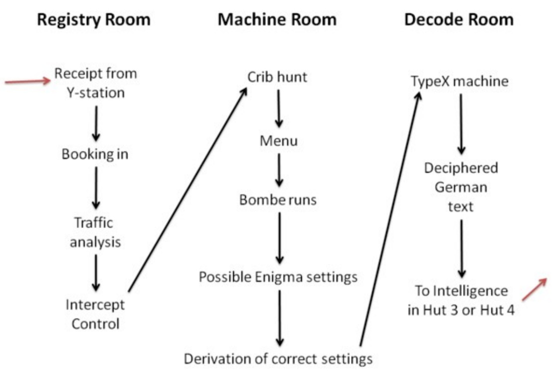
3.3 Secrecy

Properly used, the German Enigma and Lorenz ciphers should have been virtually unbreakable, but flaws in German cryptographic procedures, and poor discipline among the personnel carrying them out, created vulnerabilities which made Bletchley's attacks just barely feasible. These vulnerabilities, however, could have been remedied by relatively simple improvements in enemy procedures,[33] and such changes would certainly have been implemented had Germany any hint of Bletchley's success. Thus the intelligence Bletchley produced was considered wartime Britain's "Ultra secret" – higher even than the normally highest classification *Most Secret* [34] – and security was paramount.

Few outside Bletchley knew its mission, and even fewer (inside or outside) understood the breadth of that mission and the extent of its success. All staff signed the Official Secrets Act (1939) and a 1942 security warning emphasised the importance of discretion even within Bletchley itself: "Do not talk at meals. Do not talk in the transport. Do not talk travelling. Do not talk in the billet. Do not talk by your own fireside. Be careful even in your Hut
..."[35]

In addition, any commander in the field receiving Ultra intelligence was fed a cover story crediting a non-Ultra source; at times sham scouting missions – intentionally visible to the enemy – were dispatched to "discover" German positions in fact already known from Ultra. In some cases it was impossible to act on Ultra intelligence at all because to do so might suggest to the enemy that their communications had been penetrated,. Certain claims that the British authorities refused, for this reason, to take steps to protect civilians from imminent harm have however been vigorously disputed – with e.g. the specific claim on the Coventry Blitz now fully discredited.

3.4 Early work



Flow of information from an intercepted Enigma message[36]

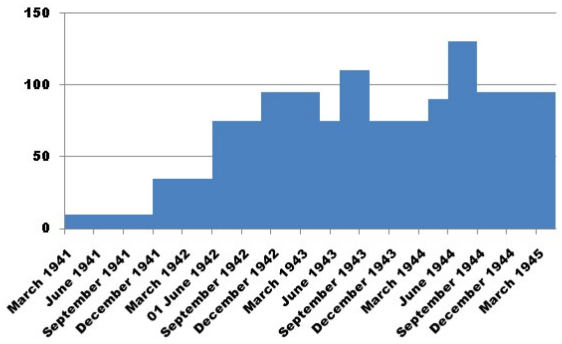
Turing, Knox, and Jeffreys did their early work in Number 3 Cottage.

The first personnel of the Government Code and Cypher School (GC&CS) moved to Bletchley Park on 15 August 1939. The Naval, Military, and Air Sections were on the ground floor of the mansion, together with a telephone exchange, teleprinter room, kitchen, and dining room; the top floor was allocated to MI6. Construction of the wooden huts began, and Elmers School, a neighbouring boarding school, was acquired for the Commercial and Diplomatic Sections.[37]

After the United States joined the war a number of American cryptographers were posted to Hut 3, and from May 1943 onwards there was close co-operation between British and American intelligence.[38] (See 1943 BRUSA Agreement.) In contrast the Soviet Union was never officially told of Bletchley Park and its activities – a reflection of Churchill's distrust of the Soviets even during the US-UK-USSR alliance imposed by the Nazi threat.

The only direct enemy damage to the site was done 20–21 November 1940 by three bombs probably intended for Bletchley railway station; Hut 4, shifted two feet off its foundation, was winched back into place as work inside continued.[39]

3.5 Intelligence reporting



Signals to Commands Abroad [40]

Non-naval Enigma messages were deciphered in Hut 6, followed by translation, indexing and cross-referencing, in Hut 3. Only then was it sent out to the Secret Intelligence Service (MI6), the intelligence chiefs in the relevant ministries, and later on to high-level commanders in
the field.[41]

Naval Enigma deciphering was in Hut 8, with translation in Hut 4. Verbatim translations were sent only to the Naval Intelligence Division (NID) of the Admiralty's Operational Intelligence Centre (OIC), supplemented by information from indexes as to the meaning of technical terms and cross-references from a knowledge store of German naval technology.[42]

Hut 4 also decoded a manual system known as the dockyard cipher, which sometimes carried messages that were also sent on an Enigma network. Feeding these back to

3.7. ADDITIONAL BUILDINGS

Hut 8 provided excellent "cribs" for Known-plaintext attacks on the daily naval Enigma key.[43]

3.6 Listening stations

Initially, a wireless room was established at Bletchley Park. It was set up in the mansion's water tower under the code name "Station X",[44] a term now sometimes applied to the codebreaking efforts at Bletchley as a whole. The "X" is the Roman numeral "ten", this being the Secret Intelligence Service's tenth such station. Due to the long radio aerials stretching from the wireless room, the radio station was moved from Bletchley Park to nearby Whaddon Hall to avoid drawing attention to the site.[45][46]

Subsequently, other listening stations – the Y-stations, such as the ones at Chicksands in Bedfordshire, Beaumanor Hall, Leicestershire (where the headquarters of the War Office "Y" Group was located) and Beeston Hill Y Station in Norfolk – gathered raw signals for processing at Bletchley. Coded messages were taken down by hand and sent to Bletchley on paper by motorcycle despatch riders or (later) by teleprinter. Bletchley Park is mainly remembered for breaking the German Enigma cypher, but its greatest cryptographic achievement may have been the breaking of the German on-line teleprinter Lorenz cipher (known at GC&CS as *Tunny*).

3.7 Additional buildings

The wartime needs required the building of additional accommodation.[47]

3.7.1 Huts

Hut 1

Often a hut's number became so strongly associated with the work performed inside that even when the work was

Hut 4, adjacent to the mansion, is now a bar and restaurant for the museum.

Hut 6 in 2004

moved to another building it was still referred to by the original "Hut" designation.[48][49] are:

- *Hut 1*: The first hut, built in 1939[50] used to house the Wireless Station for a short time,[44] later administrative functions such as transport, typing, and Bombe maintenance. The first Bombe, "Victory", was initially housed here.[51]
- *Hut 2*: A recreational hut for "beer, tea, and relaxation".[52]
- *Hut 3*: Intelligence: translation and analysis of Army and Air Force decrypts[53]
- *Hut 4*: Naval intelligence: analysis of Naval Enigma and Hagelin decrypts[54]
- *Hut 5*: Military intelligence including Italian, Spanish, and Portuguese ciphers and German police codes.[55]
- *Hut 6*: Cryptanalysis of Army and Air Force Enigma[56]

- *Hut 7*: Cryptanalysis of Japanese naval codes and intelligence.[57][58]

- *Hut 8*: Cryptanalysis of Naval Enigma.[42]
- *Hut 9*: ISOS (Intelligence Section Oliver Strachey).

- *Hut 10*codes, Air and Meteorological sections.: Secret Intelligence Service (SIS or MI[59] 6)

- *Hut 11*: Bombe building.[60]

- *Hut 14*: Communications centre.[61]

- *Hut 15*Analysis).: SIXTA (Signals Intelligence and

Traffic • phers.*Hut 16*: ISK (Intelligence Service

Knox) Abwehr ci-

- *Hut 18*: ISOS (Intelligence Section Oliver Strachey).

- *Hut 23*partment. After February 1943, Hut 3 was renamed: Primarily used to house the engineering de-

  Hut 23 (the reason it was not named Hut 13 in a similar way to the other huts, was due to the belief that the number 13 was unlucky).

3.7.2 Blocks

In addition to the wooden huts there were a number of brick-built "blocks".

- *Block A*: Naval Intelligence.

- *Block B*breaking.: Italian Air and Naval, and Japanese code

- *Block C*: Stored the substantial punch-card index.

- *Block D*and 8. : Enigma work, extending that in huts 3, 6,

- *Block E*and TypeX.:IncomingandoutgoingRadioTransmission

- Japanese Military Air Section. It has since been

  de-*Block F*: Included the Newmanry and Testery,

  and molished.

- *Block G*: Traffic analysis and deception operations.

- *Block H*Museum of Computin: *Tunny* and Colossus (nowg). The National

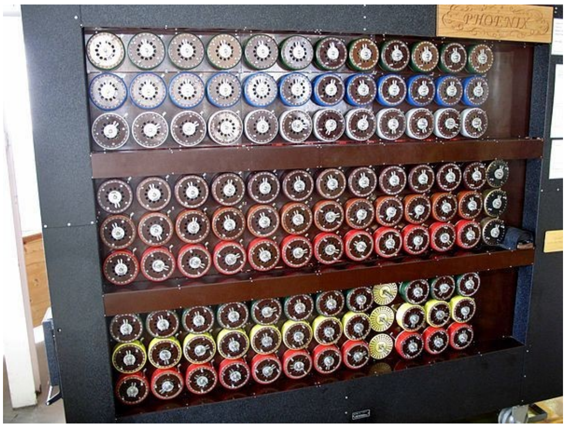
3.8 Work on specific countries' signals

3.8.1 German signals

Most German messages decrypted at Bletchley were produced by one or another version of the Enigma cipher machine, but an important minority were produced by the even more complicated twelve-rotor Lorenz SZ42 on-line teleprinter cipher machine.

Bletchley's Polish Memorial, commemorating "the [prewar] work of Marian Rejewski, Jerzy Różycki and Henryk Zygalski, mathematicians of the Polish intelligence service, in first breaking the Enigma code. Their work greatly assisted the Bletchley Park code breakers and contributed to the Allied victory in World War II."

Five weeks before the outbreak of war, in Warsaw's Cipher Bureau revealed its achievements in breaking Enigma to astonished French and British personnel.[33] The British used the Poles' information and techniques, and the Enigma clone sent to them in August 1939, which greatly increased their (previously very limited) success in decrypting Enigma messages.[62]



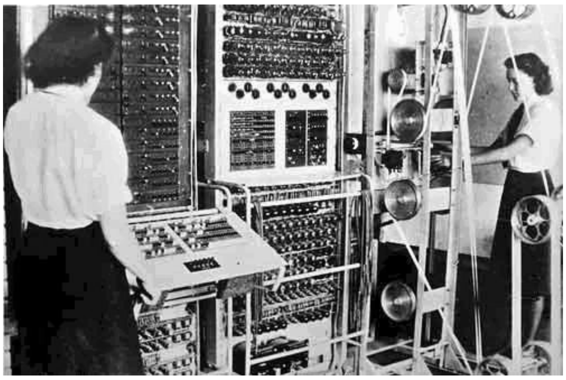
The working rebuilt bombe, built by a team led by John Harper[63] and switched on by the Duke of Kent, patron of the British Computer Society, on 17 July 2008

The bombe was an elec tro mech anic al device whose function was to discover some of the daily settings of the Enigma machines on the various German military networks.[64][65][66] Its pioneering design was developed by Alan Turing (with an important contribution from Gordon Welchman) and the machine was engineered by Harold 'Doc' Keen of the British Tabulating Machine Company. Each machine was about 7 feet (2.1 m) high and wide, 2 feet (0.61 m) deep and weighed about a ton.[67]

At its peak, GC&CS was reading approximately 4,000 messages per day.[68] As a hedge against enemy attack[69] most bombes were dispersed to installations at Adstock and Wavendon (both later supplanted by installations at Stanmore and Eastcote), and Gayhurst.[70][71]

Luftwaffe messages were the first to be read in quantity.

The German navy had much tighter procedures, and the capture of code books was needed before they could be broken. When, in February 1942, the German navy introduced the four-rotor Enigma for communications with its Atlantic U-boats, this traffic became unreadable for a period of ten months.[72] Britain produced modified bombes, but it wasthe success of the US Navy bombe that was the main source of reading messages from this versionofEnigmafortherestofthewar.
Messageswerесent to and fro across the Atlantic by enciphered teleprinter links.



A Mark 2 Colossus computer. The ten Colossi were the world's first (semi-) programmable electronic computers, the first having been built in 1943

The Lorenz messages were codenamed *Tunny* at Bletchley Park. They were only sent in quantity from mid1942. The Tunny networks were used for high-level messages between German High Command and field commanders. With the help of German operator errors, the cryptanalysts in the Testery (named after Ralph Tester, its head) worked out the logical structure of the machine despite not knowing its physical form. They devised automatic machinery to help with decryption, which culminated in Colossus, the world's first programmable digital electronic computer. This was designed and built by Tommy Flowers and his team at the Post Office Research Station at Dollis Hill. The prototype first worked in December 1943, was delivered to Bletchley Park in January and first worked operationally on 5 February 1944. Enhancements were developed for the Mark 2 Colossus, the first of which was working at Bletchley Park on the morning of 1 June in time for D-day. Flowers then produced one Colossus a month for the rest of the war, making a total of ten with an eleventh part-built. The machines were operated mainly by Wrens in a section named the Newmanry after its head Max Newman.

Bletchley's work was essential to defeating the U-boats in the Battle of the Atlantic, and to the British naval victories in the Battle of Cape Matapan and the Battle of North Cape. In 1941, Ultra exerted a powerful effect on the North African desert campaign against German forces under General Erwin Rommel. General Sir Claude Auchinleck wrote that were it not for Ultra, "Rommel would have certainly got through to Cairo".
While not changing the events, "Ultra" decrypts featured prominently in the story of Operation SALAM, László Almásy's daring mission across the Libyan Desert behind enemy lines in 1942.[73] Prior to the Normandy landings on D-Day in June 1944, the Allies knew the locations of all but two of Germany's fifty-eight Western-front divisions.

3.8.2 Italian signals

See also: Cryptanalysis of the Enigma

Italian signals had been of interest since Italy's attack on Abyssinia in 1935. During the Spanish Civil War the Italian Navy used the K model of the commercial Enigma without a plugboard; this was solved by Knox in 1937. When Italy entered the war in 1940 an improved version of the machine was used, though little traffic was sent by it and there were "wholesale changes" in Italian codes and cyphers. Knox was given a new section for work on Enigma variations, which he staffed with women ("Dilly's girls") who included Margaret Rock, Jean Perrin, Clare Harding, Rachel Ronald, Elisabeth Granger; and Mavis Lever[74] – who made the first break into the Italian naval traffic. She solved the signals revealing the Italian Navy's operational plans before the Battle of Cape Matapan in 1941, leading to a British victory. Although most Bletchley staff did not know the results of their work, Admiral Cunningham visited Bletchley in person a few weeks later to congratulate them.[75]

On entering World War II in June 1940, the Italians were usingbookcodesformostoftheirmilitarymessages. The exception was the Italian Navy, which after the Battle of Cape Matapan started using the C-38 version of the Boris Hagelin rotor-based cipher machine, particularly to route their navy and merchant marine convoys to the conflict in NorthAfrica.[76] Asaconsequence, JRMButlerrecruited his former student Bernard Willson to join a team with two others in Hut 4.[77][78] In June 1941, Willson became the first of the team to decode the Hagelin system, thus enabling military commanders to direct the Royal Navy andRoyalAirForcetosinkenemyshipscarryingsupplies from Europe to Rommel's Afrika Korps. This led to increased shipping losses and, from reading the intercepted traffic, the team learnt that between May and September 1941 the stock of fuel for the Luftwaffe in North Africa reduced by 90%.[79] After an intensive language course, in March 1944 Willson switched to Japanese languagebased codes.[80]

A Middle East Intelligence Centre (MEIC) was set up in Cairo in 1939. When Italy entered the war in June 1940, delays in forwarding intercepts to Bletchley via congested radio links resulted in cryptanalysts being sent to Cairo. A Combined Bureau Middle East (CBME) was set up in November, though the Middle East authorities made "increasingly bitter complaints" that GC&CS was giving too little priority to work on Italian cyphers. However, the principle of concentrating high-grade cryptanalysis at Bletchley was maintained.[81] John Chadwick started cryptanalysis work in 1942 on Italian signals at the naval base 'HMS Nile' in Alexandria. Later he was with GC&CS; in the Heliopolis Museum, Cairo and then in the Villa Laurens, Alexandria.

3.8.3 Soviet signals

Soviet signals had been studied since the 1920s. In 1939– 40 John Tiltman (who had worked on Russian Army traffic from 1930) set up two Russian sections at Wavendon (a country house near Bletchley) and at Sarafand in Palestine. Two Russian high-grade army and navy systems were broken. Tiltman spent two weeks in Finland, where he obtained Russian traffic from Finland and Estonia in exchange for radio equipment. In June 1941 when the Soviet Union became an ally, Churchill ordered a halt to intelligence operations against it. In December 1941 the Russian section was closed down, but in late summer 1943 or late 1944 a small GC&CS Russian cypher section was set up in London overlooking Park Lane then in Sloane Square.[82]

3.8.4 Japanese signals

An outpost of the Government Code and Cypher School had been set up in Hong Kong in 1935, the Far East Combined Bureau (FECB). The FECB naval staff moved in 1940 to Singapore, then Colombo, Ceylon, then Kilindini, Mombasa, Kenya. They succeeded in deciphering Japanese codes with a mixture of skill and good fortune.[83] The Army and Air Force staff went from Singapore to the Wireless Experimental Centre at Delhi, India.

In early 1942, a six-month crash course in Japanese, for 20 undergraduates from Oxford and Cambridge, was started by the Inter-Services Special Intelligence School in Bedford, in a building across from the main Post Office. This course was repeated every six months until war's end. Most of those completing these courses worked on decoding Japanese naval messages in Hut 7, under John Tiltman.

By mid-1945 well over 100 personnel were involved with this operation, which co-operated closely with the FECB and the US Signal intelligence Service at Arlington Hall, Virginia. Because of these joint efforts, by August of that year the Japanese merchant navy was suffering 90% losses at sea. In 1999, Michael Smith wrote that: "Only now are the British codebreakers (like John Tiltman, Hugh Foss, and Eric Nave) beginning to receive the recognition they deserve for breaking Japanese codes and cyphers".[84]

3.9 Post war

3.9.1 Continued secrecy

Much of Bletchley's equipment and documents was destroyed at the end of the war, and the secrecy imposed on Bletchley staff remained in force, so that most relatives never knew more than that a child, spouse, or parent had done some kind of secret war work,[85] or were told a cover story about clerical or statistical work.

Churchill referred to the Bletchley staff as “the geese that laid the golden eggs and never cackled”.[86] That said, occasional mentionsoftheworkperformedatBletchleyParkslipped the censor’s net and appeared in print.[87]

With the publication of F. W. Winterbotham’s *The Ultra Secret* (1974)[88] public discussion of Bletchley’s work finally became possible (though even today some former staff still consider themselves bound to silence)[89] and in July 2009 the British government announced that Bletchleypersonnelwouldberecognisedwithacommemor ative badge.[90]

3.9.2 Site

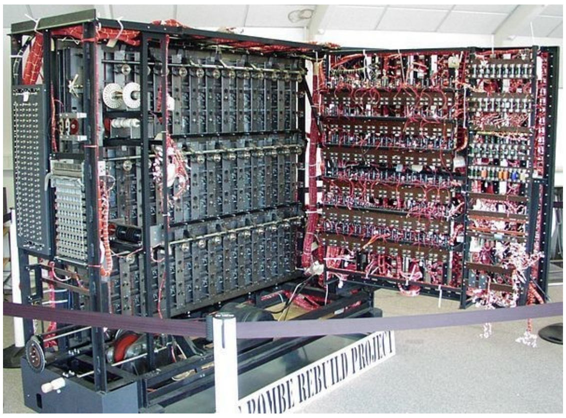
After the war, the site passed through a succession of hands[91] and saw a number of uses, including as a teacher-training college and local GPO headquarters. By 1991, the site was nearly empty and the buildings were at risk of demolition for redevelopment.

In February 1992, the Milton Keynes Borough Council declared most of the Park a conservation area, and the Bletchley Park Trust was formed to maintain the site as a museum. The site opened to visitors in 1993, and was formally inaugurated by HRH The Duke of Kent as Chief Patron in July 1994. In 1999, the Trust concluded an agreement with the landowner, giving control over much of the site to the Trust.[92]

3.10 Bletchley Park as a heritage attraction

June 2014 saw the completion of an £8 million restoration project, which was marked by a visit from Catherine, Duchess of Cambridge. The Duchess’ paternal grandmother, Valerie, and Valerie’s twin sister, Mary (née Glassborow) both worked at Bletchley Park during the war. The twin sisters worked as Foreign Office Civilians in Hut 6, where they managed the interception of enemy and neutral diplomatic signals for decryption. Valerie married Catherine’s grandfather Peter Middleton, who was a civilian staff member at Bletchley.[94][95][96]

3.11. FUNDING



View of the back of the rebuilt Bombe[93]

3.10.1 Exhibitions

- Block C Visitor Centre
- Secrets Revealed introduction • The Road to

  Bletchley Park. Codebreaking inWorld War

  One.
- Intel Security Cybersecurity exhibition. On-line security and privacy in the 21st Century.
- Block B
- Operational Bombe Rebuild
- Lorenz Cipher
- Alan Turing
- Enigma machines
- Japanese codes
- Home Front exhibition. How people lived inWW2
- The Mansion • Office of Alistair Denniston
- Library. Dressed as a WW2 naval intelligenceoffice
- The Imitation Game exhibition
- Gordon Welchman: Architect of Ultra Intelli-gence exhibition

- Huts 3 and 6. Codebreaking offices as they wouldhave looked during WW2.

- Hut 8.

- Interactive exhibitions explaining

codebreak-ing • Alan Turing's office

- Pigeon exhibition.WW2. The use of pigeons in

- Hut 11. Life as a WRNS Bombe operator
- Hut 12. Bletchley Park: Rescued and Restored.

Items found during the restoration work.

- Wartime garages

3.11 Funding

In October 2005, American billionaire Sidney Frank donated £500,000 to Bletchley Park Trust to fund a new Science Centre dedicated to Alan Turing.[97] In July 2008 a letter to The Times from more than a hundred academics condemned the neglect of the site.[98][99] In September 2008, PGP, IBM, and other technology firms announced a fund-raising campaign to repair the facility.[100] On 6 November 2008 it was announced that English Heritage would donate £300,000 to help maintain the buildings at Bletchley Park, and that they were in discussions regarding the donation of a further £600,000.[101]

In October 2011, the Bletchley Park Trust received a £4.6m Heritage Lottery Fund grant to be used "to complete the restoration of the site, and to tell its story to the highest modern standards.", on the condition that £1.7m of 'match funding' is raised by the Bletchley Park Trust.[102][103] Just weeks later Google contributed £550k[104] and by June 2012 the trust had successfully raised £2.4m to unlock the grants to restore Huts 3 and 6, as well as develop its exhibition centre in Block C.[105]

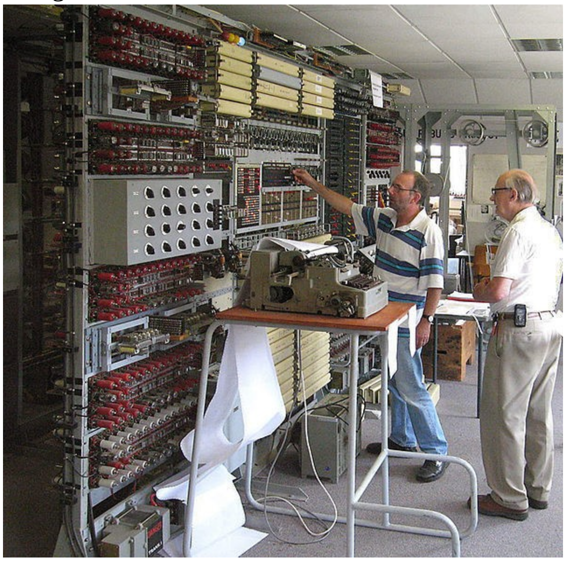
Additional income is raised by renting Block H to the National Museum of Computing, and some office space in
various parts of the park to private firms.[106][107][108]

3.12 Other organisations sharing the campus

3.12.1 National Museum of Computing

Main article: The National Museum of Computing The National Museum of Computing is housed in Block H, which is rented from the Bletchley Park Trust. Its Colossus and Tunny galleries tell an important part of allied breaking of German codes during World War II. There is a working reconstruction of a Colossus computer that was used on the high-level Lorenz cipher, codenamed *Tunny* by the British.[109]

The museum, which opened in 2007, is an independent voluntary organisation that is governed by its own board of trustees. Its aim is "To collect and restore computer systems particularly those developed in Britain and to enable people to explore that collection for inspiration, learning and enjoyment."[110] Through its many exhibits, the museum displays the story of computing through the mainframes of the 1960s and 1970s, and the rise of personal computing in the 1980s. It has a policy of having as many of the exhibits as possible in full working order.



Tony Sale supervising the breaking of an enciphered message with the completed Colossus computer rebuild in 2006

The Colossus and Tunny galleries are open daily. The rest of the Museum is open to the public every Thursday, Saturday and Sunday afternoons and most bank holidays, and by appointment for groups only, at other times. There are guided tours on Tuesday afternoons. There is a modest admission charge to the museum to help cover overheads.

3.12.2 RSGB National Radio Centre

The Radio Society of Great Britain's National Radio Centre (including a library, radio station, museum and bookshop) are in a newly constructed building on Bletchley's grounds. [111][112]

3.13 In popular culture

German U-boat model used in the film Enigma (2001)

3.13.1 Film

- The film *Enigma* (2001), starring Kate Winslet, Saffron Burrows and Dougray Scott, is set in part in Bletchley Park.
- The film *The Imitation Game* (2014), starring Benedict Cumberbatch as Alan Turing, is set in Bletchley Park.

3.13.2 Literature

- Bletchley featured heavily in Robert Harris' novel *Enigma* (1995) and its eponymous 2001 film adaptation, although filming was done at nearby Chicheley Hall. (See photograph)
- A fictionalised version of Bletchley Park is featured in Neal Stephenson's novel *Cryptonomicon* (1999).
- Bletchley Park plays a significant role in Connie Willis' novel *All Clear* (2010).

3.13.3 Television

- The 1979 ITV television serial *Danger UXB* featured the character Steven Mount, who was a codebreaker at Bletchley and was driven to a nervous breakdown (and eventual suicide) by the stressful and repetitive nature of the work.
- In *Foyle's War*, Adam Wainwright (Samantha Stewart's fiance, then husband), is a former Bletchley Park codebreaker.[113][114][115]
- The Second World War code-breaking sitcom pilot "Satsuma & Pumpkin" was recorded at Bletchley Park in 2003 and featured Bob Monkhouse, OBE in his last ever screen role. The BBC declined to produce the show and develop it further before creating effectively the same show on Radio 4 several years later, featuring some of the same cast, entitled *Hut 33*.[116] [117]
- Bletchley came to wider public attention with the documentary series *Station X* (1999).
- The 2012 ITV programme, *The Bletchley Circle*, is a set of murder mysteries set in 1952 and 1953. The protagonists are four female former Bletchley codebreakers, who use their skills to solve crimes. The pilot episode's opening scene was filmed on-site, and the set was asked to remain there for its close adaptation of historiography.[118][119]
- Ian McEwan's television play *The Imitation Game* (1980) concludes at Bletchley Park.
- Bletchley Park was featured in the sixth and final episode of the BBC TV documentary *The Secret War* (1977), presented and narrated by William Woodard. This episode featured interviews with Gordon Welchman, Harry Golombek, Peter Calvocoressi, F. W. Winterbotham, Max Newman, Jack Good, and Tommy Flowers.

3.13.4 Theatre

- The play *Breaking the Code* (1986) is set at Bletch-

3.13.5 Video Games

- Bletchley is featured in a level of the Russian videogame *Death to Spies: Moment of Truth*. The player, a Soviet spy working for SMERSH, is tasked with killing a professor at the park, and stealing a briefcase pertaining to Bletchley's code-breaking of Soviet communications.

3.14 See also

- Arlington Hall
- Beeston Hill Y Station

- Danesfield House
- then Singapore, Colombo (Ceylon) and KilindiniFar East Combined Bureau in Hong Kong prewar,

  (Kenya)
- List of people associated with Bletchley Park
- National Cryptologic Museum
- Newmanry
- Washington, D.C.OP-20-G, the US Navy's cryptanalysis office in
- Testery
- Wireless Experimental CentrIntelligence Corps outside Delhei operated by the
- Y-stations

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Chapter 4

Government Communications Headquarters

NottobeconfusedwithHerMajesty'sGovernmentCommunications Centre.
"GCHQ" redirects here. It is not to be confused with CCHQ.
The **Government Communications Headquarters**

"The Doughnut", the headquarters of the GCHQ.

(**GCHQ**) is a British intelligence and security organisation responsible for providing signals intelligence (SIGINT) and information assurance to the British government and armed forces.[2] Based in "The Doughnut", in the suburbs of Cheltenham, it operates under the formal direction of the Joint Intelligence Committee (JIC) alongside the Security Service (MI5), the Secret Intelligence Service (MI6) and Defence Intelligence (DI). GCHQ is the responsibility of the UK Secretary of State for Foreign and Commonwealth Affairs, but it is not a part of the Foreign Office and its Director ranks as a Permanent Secretary.

GCHQ was originally established after the First World War as the *Government Code and Cypher School* (GC&CS) and was known under that name until 1946. During the Second World War it was located at Bletchley Park, where it was famed for its role in the breaking of the German Enigma codes. Currently there are two main components of the GCHQ, the Composite Signals Organisation (CSO), which is responsible for gathering information, and the CESG, which is responsible for securing the UK's own communications. The Joint Technical Language Service (JTLS) is a small department and cross-government resource responsible for mainly technical language support and translation and interpreting services across government departments. It is co-located with GCHQ for administrative purposes.

In 2013, GCHQ received considerable media attention when the former National Security Agency contractor Edward Snowden revealed that the agency was in the process of collecting all online and telephone data in the UK via the Tempora programme.[3] Snowden's revelations began a spate of ongoing disclosures of global surveillance.

4.1 Structure

GCHQ is led by the Director of GCHQ, currently Robert Hannigan, and a Corporate Board, made up of Executive and Non-Executive Directors. Reporting to the Corpo-
rate Board is:[4][5]

- Sigint missions: comprising maths and cryptanalysis, IT and computer systems, linguistics and translation, and the intelligence analysis unit
- Enterprise: comprising applied research and emerging technologies, corporate knowledge and information systems, commercial supplier relationships, and biometrics

- Corporate management: enterprise resource planning, human resources, internal audit, and architecture

- Communications-Electronics Security Group

4.2 History

4.2.1 Government Code and Cypher School (GC&CS)

During the First World War, the United Kingdom's Army and Navy had separate signals intelligence agencies, MI1b and NID25 (initially known as Room 40) respectively.[6][7] In 1919, the Cabinet's Secret Service Committee, chaired by Lord Curzon, recommended that a peace-time codebreaking agency should be created, a task given to the then-Director of Naval Intelligence, Hugh Sinclair.[8] Sinclair merged staff from NID25 and MI1b into the new organisation, which initially consisted of around 25–30 officers and a similar number of clerical staff.[9] It was titled the "Government Code and Cypher School", a cover-name chosen by Victor Forbes of the Foreign Office.[10] Alastair Denniston, who had been a member of NID25, was appointed as its operational head.[8] It was initially under the control of the Admiralty, and located in Watergate House, Adelphi, London.[8] Its public function was "to advise as to the security of codes and cyphers used by all Government departments and to assist in their provision", but also had a secret directive to "study the methods of cypher communications used by foreign powers".[11] GC&CS officially formed on 1 November 1919,[12] and produced its first decrypt on 19 October.[8]

Allidina Visram school in Mombasa, pictured above in 2006, was the location of the British "Kilindini" codebreaking outpost during World War II

Before the Second World War, GC&CS was a relatively small department. By 1922, the main focus of GC&CS was on diplomatic traffic, with "no service traffic ever worth circulating"[13] and so, at the initiative of Lord Curzon, it was transferred from the Admiralty to the Foreign Office.[14] GC&CS came under the supervision of Hugh Sinclair, who by 1923 was both the Chief of SIS and DirectorofGC&CS.[8] In1925, both organisationswerecolocated on different floors of Broadway Buildings, opposite St. James's Park.[8] Messages decrypted by GC&CS were distributed in blue-jacketed files that became known as "BJs".[15]

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In the 1920s, GC&CS was successfully reading Soviet Union diplomatic ciphers. However, in May 1927, during a row over clandestine Soviet support for the General Strike and the distribution of subversive propaganda, Prime Minister Stanley Baldwin made details from the decrypts public.[16]

Main article: Ultra (cryptography)

During the Second World War, GC&CS was based largely at Bletchley Park in present-day Milton Keynes working on, most famously, the German Enigma machine and Lorenz ciphers,[17] but also a large number of other systems. In 1940, GC&CS was working on the diplomatic codes and ciphers of 26 countries, tackling over 150 diplomatic cryptosystems.[18] Senior staff included Alastair Denniston, Oliver Strachey, Dilly Knox, John Tiltman, Edward Travis, Ernst Fetterlein, Josh Cooper, DonaldMichie, AlanTuring, JoanClarke, MaxNewman, William Tutte, I. J. (Jack) Good, Peter Calvocoressi and Hugh Foss.

An outstation in the Far East, the Far East Combined Bureau was set up in Hong Kong in 1935, and moved to Singapore in 1939. Subsequently with the Japanese advance down the Malay Peninsula, the Army and RAF codebreakers went to the Wireless Experimental Centre in Delhi, India. The Navy codebreakers in FECB went to Colombo, Ceylon, then to Kilindini, near Mombasa, Kenya.

GC&CS was renamed the "Government Communications Headquarters" in June 1946.[19]

4.2.2 Post Second World War

GCHQ was at first based in Eastcote, but in 1951[20] moved to the outskirts of Cheltenham, setting up two sites there – Oakley and Benhall. GCHQ had a very low profile in the media until 1983 when the trial of Geoffrey Prime, a KGB mole within GCHQ, created considerable media interest.[21]

Since the days of the Second World War, US and British intelligence have shared information. For the GCHQ this means that it shares information with, and gets information from, the National Security Agency (NSA) in the United States.[22]

Public key encryption

Early in the 1970s, the concept for public key encryption was developed and proven by James H. Ellis, a GCHQ staff member since 1952, who lacked the necessary number theory expertise necessary to build a workable system. Subsequently a feasible implementation scheme via an asymmetric key algorithm was invented by another staff member Clifford Cocks, a mathematics graduate. This fact was kept secret until 1997.[23]

Trade union disputes

NUCPS banner on march in Cheltenham 1992

Main article: Council of Civil Service Unions v Minister for the Civil Service

In 1984, GCHQ was the centre of a political row when the Conservative government of Margaret Thatcher prohibited its employees from belonging to a trade union. It was claimed that joining a union would be in conflict with national security. A number of mass national one-day strikes were held to protest this decision, seen as a first step to wider bans on trade unions. Appeals to British Courts and European Commission of Human Rights[24] were unsuccessful. The government offered a sum of money to each employee who agreed to give up their union membership. Appeal to the ILO resulted in a decision that government's actions were in violation of Freedom of Association and Protection of the Right to Organise Convention.[25] The ban was eventually lifted by the incoming Labour government in 1997, with the Government Communications Group of the Public and Commercial Services (PCS) Union being formed to represent interested employees at all grades.[26] In 2000, a group of 14 former GCHQ employees, who had been dismissed after refusing to give up their union membership, were offered re-employment, which three of them accepted.[27]

4.2.3 Post Cold War

1990s: Post-Cold War restructuring

The Intelligence Services Act 1994 placed the activities of the intelligence agencies on a legal footing for the first time, defining their purpose, and the British Parliament's Intelligence and Security Committee was given a remit to examine the expenditure, administration and policy of the three intelligence agencies.[28] The objectives of GCHQ were defined as working as "in the interests of national security, with particular reference to the defence and foreign policies of Her Majesty's government; in the interests of the economic wellbeing of the United Kingdom; and in support of the prevention and the detection of serious crime".[29] During the introduction of the Intelligence Agency Act in late 1993, the former Prime Minister Jim Callaghan had described GCHQ as a "full blown bureaucracy", adding that future bodies created to provide oversight of the intelligence agencies should "investigate whether all the functions that GCHQ carries out today are still necessary."[30]

In 1993, in the wake of the "Squidgygate" affair, GCHQ denied "intercepting, recording or disclosing" the telephone calls of the British Royal family.[31]

In late 1993 civil servant Michael Quinlan advised a deep review of the work of GCHQ following the conclusion of his "Review of Intelligence Requirements and Resources", which had imposed a 3% cut on the agency.[32] The Chief Secretary to the Treasury, Jonathan Aitken, subsequently held face to face discussions with the intelligence agency directors to assess further savings in the wake of Quinlan's review. Aldrich (2010) suggests that Sir John Adye, the then Director of GCHQ performed badly in meetings with Aitken, leading Aitken to conclude that GCHQ was "suffering from out-of-date methods of management and out-of-date methods for assessing priorities".[33] GCHQ's budget was £850 million in 1993, (£1.55 billion) as of 2016)[34] compared to £125 million for MI5 and SIS. In December 1994 the businessman Roger Hurn was commissioned to begin a review of GCHQ, which was concluded in March 1995.[35] Hurn's report recommended a cut of £100 million in GCHQ's budget, such a large reduction had not been suffered by any British intelligence agency since the end of World War II.[35] The J Division of GCHQ, which had collected SIGINT on Russia, disappeared as result of the cuts.[35] The cuts had been mostly reversed by 2000 in the wake of threats from violent non-state actors, and risks from increased terrorism, organised crime and illegal access to nuclear, chemical and biological weapons.[36]

David Omand became the Director of GCHQ in 1996, and greatly restructured the agency in the face of new and changing targets and rapid technological change.[37] Omand introduced the concept of "Sinews" (or "SIGINT New Systems") which allowed more flexible working methods, avoiding overlaps in work by creating fourteen domains, each with a well-defined working scope.[37] The tenure of Omand also saw the planning and the creation of The Doughnut, GCHQ's modern headquarters.[37] Located on a 176-acre site in Benhall, near Cheltenham, The Doughnut would be the largest building constructed for secret intelligence operations outside the United States.[38]

Operations at GCHQ's Chum Hom Kwok listening station in Hong Kong ended in 1994.[39] GCHQ's Hong Kong operations were extremely important to their rela-

tionship with the NSA, who contributed investment and equipment to the station. In anticipation of the transfer of Hong Kong to the Chinese government in 1997, the Hong Kong stations operations were moved to Geraldton in Australia.[40]

Operations that utilised GCHQ's intelligence-gathering capabilities in the 1990s included the monitoring of communications of Iraqi soldiers in the Gulf War, of dissident republican terrorists and the Real IRA, of the various factions involved in the Yugoslav Wars, and of the criminal Kenneth Noye.[36][40][41] In the mid 1990s GCHQ began to assist in the investigation of cybercrime.[42]

2000s: Coping with the Internet

See also: Global surveillance and Global surveillance disclosures (2013–present)

At the end of 2003, GCHQ moved to a new circular HQ (popularly known as "The Doughnut"): at the time, it was the second-largest public-sector building project in Europe, with an estimated cost of £337 million. The new building, which was designed by Gensler and constructed by Carillion,[43] is the base for all of GCHQ's Cheltenham operations.

The public spotlight fell on GCHQ in late 2003 and early 2004 following the sacking of Katharine Gun after she leaked to *The Observer* a confidential email from agents at the United States' National Security Agency addressed to GCHQ agents about the wiretapping of UN delegates in the run-up to the 2003 Iraq war.[44]

GCHQ gains its intelligence by monitoring a wide variety of communications and other electronic signals. For this, a number of stations have been established in the UK and overseas. The listening stations are at Cheltenham itself, Bude, Scarborough, Ascension Island, and with the United States at Menwith Hill.[45] Ayios Nikolaos Station in Cyprus is run by the British Army for GCHQ.[46]

In March 2010, GCHQ was criticised by the Intelligence and Security Committee for problems with its IT security practices and failing to meet its targets for work targeted against cyber attacks.[47]

As revealed by Edward Snowden in *The Guardian*, GCHQ spied on foreign politicians visiting the 2009 G-20 London Summit by eavesdropping phonecalls and emails and monitoring their computers, and in some cases even ongoing after the summit via keyloggers that had been installed during the summit.[48] Some of the information gained has been passed on to British politicians.

According to Edward Snowden, GCHQ has two principal umbrella programs for collecting communications:

- "Mastering the Internet" (MTI) for Internet traffic, which is extracted from fiber-optic cables and can be searched by using the Tempora computer system.
- "Global Telecoms Exploitation" (GTE) for telephone traffic.[49]

GCHQ also has had access to the US internet monitoring programme PRISM since at least June 2010.[50] PRISM is said to give the National Security Agency and FBI easy access to the systems of nine of the world's top internet companies, including Google, Facebook, Microsoft, Apple, Yahoo, and Skype.[51]

In February 2014, *The Guardian*, based on documents provided by Snowden, revealed that GCHQ had indiscriminately collected 1.8 million private Yahoo webcam images from users across the world.[52] In the same month NBC and The Intercept, based on documents released by Snowden, revealed the Joint Threat Research Intelligence Group and the CNE units within GCHQ. Their mission was cyber operations based on "dirty tricks" to shut down enemy communications, discredit, and plant misinformation on enemies.[53] These operations were 5% of all GCHQ operations according to a conference slideshow presented by the GCHQ.[54]

Soon after becoming Director of GCHQ in 2014, Robert Hannigan wrote an article in the *Financial Times* on the topic of internet surveillance, stating that "however much [large US technology companies] may dislike it, they have become the command and control networks of choice for terrorists and criminals" and that GCHQ and its sister agencies "cannot tackle these challenges at scale without greater support from the private sector", arguing that most internet users "would be comfortable with a better and more sustainable relationship between the [intelligence] agencies and the tech companies". Since the 2013 global surveillance disclosures, large US technology companies have improved security and become less co-operative with foreign intelligence agencies, including those of the UK, generally requiring a US court order before disclosing data.[55][56] However the head of the UK technology industry group techUK rejected these claims, stating that they understood the issues but that disclosure obligations "must be based upon a clear and transparent legal framework and effective oversight rather than, as suggested, a deal between the industry and government".[57]

In 2015, another secret program called Karma Police was revealed by Snowden.[58] The same year GCHQ has admitted for the first time in court that it conducts computer hacking.[59]

4.3 CESG

CESG (originally Communications-Electronics Security Group) is the group within GCHQ which provides assistance to government departments on their own communications security: CESG is the UK National Technical Authority for information assurance, including cryptography. CESG does not manufacture security equipment, but works with industry to ensure the availability of suitable products and services, while GCHQ itself can fund research into such areas, for example to the Centre for Quantum Computing at Oxford University and the Heilbronn Institute at the University of Bristol.[60]

CESG runs a number of assurance schemes such as CHECK, CLAS, Commercial Product Assurance (CPA) and CESG Assisted Products Service (CAPS).[61]

4.4 Joint Technical Language Service

The Joint Technical Language Service (JTLS) was established in 1955,[62] drawing on members of the small Ministry of Defence technical language team and others, initially to provide standard English translations for organisational expressions in any foreign language, discover the correct English equivalents of technical terms in foreign languages and discover the correct expansions of abbreviations in any language. The remit of the JTLS has expanded in the ensuing years to cover technical language support and interpreting and translation services across the UK Government and to local public sector services in Gloucestershire and surrounding counties. The JTLS also produces and publishes foreign language working aids under crown copyright and conducts research into machine translation and on-line dictionaries and glossaries. The JTLS is co-located with GCHQ for administrative purposes.

4.5 International relationships

See also: UKUSA Agreement and Five Eyes

GCHQ operates in partnership with equivalent agencies worldwide in a number of bi-lateral and multi-lateral relationships. The principal of these is with the United States (National Security Agency), Canada (Communications Security Establishment), Australia (Defence Signals Directorate) and New Zealand (Government Communications Security Bureau), through the mechanism of the UK-US Security Agreement, a broad intelligence-sharing agreement encompassing a range of intelligence collection methods.

Relationships are alleged to include shared collection methods, such as the system described in the popular media as ECHELON, as well as analysed product.[63]

4.6 Legal basis

Main article: Intelligence Services Act 1994

GCHQ's legal basis is enshrined in the Intelligence Services Act 1994 Section 3 as follows:

> (1) There shall continue to be a Government Communications Headquarters under the authority of the Secretary of State; and, subject to subsection (2) below, its functions shall be—
>
> (a) to monitor or interfere withelectromagnetic, acoustic and other emissions and any equipment producing such emissions and to obtain and provide information derived from or related to such emissions or equipment and from encrypted material; and
>
> (b) to provide advice and assistanceabout—
>
> (i) languages, including terminology used for technical matters, and
>
> (ii) cryptography and other matters relating to the protection of information and other material, to the armed forces of the Crown, to Her Majesty's

Government in the United Kingdom or to a Northern Ireland Department or to any other organisation which is determined for the purposes of this section in such manner as may be specified by the Prime Minister.

(2) The functions referred to in subsection (1)(a) above shall be exercisable only—

(a) in the interests of national security, with particular reference to the defence and foreign policies of Her Majesty's Government in the United Kingdom; or

(b) in the interests of the economicwell-being of the United Kingdom in relation to the actions or intentions of persons outside the British Islands; or

(c) in support of the prevention ordetection of serious crime.

(3) In thisAct the expression "GCHQ" refersto the Government Communications Headquarters and to any unit or part of a unit of the armed forces of the Crown which is for the time being required by the Secretary of State to assist the Government Communications Headquarters in carrying out its functions.[64]

Activities that involve interception of communications are permitted under the Regulation of Investigatory Powers Act 2000; this kind of interception can only be carried out after a warrant has been issued by a Secretary of State. The Human Rights Act 1998 requires the intelligence agencies, including GCHQ, to respect citizens' rights as described in the European Convention on Human Rights.[65][66][67]

4.6.1 Oversight

See also: Mass surveillance in the United Kingdom

The Prime Minister nominates cross-party Members of Parliament to an Intelligence and Security Committee. The remit of the Committee includes oversight of intelligence and security activities and reports are made directly to Parliament.[68] Its functions were increased under the Justice and Security Act 2013 to provide for further access and investigatory powers.

Judicial oversight of GCHQ's conduct is exercised by the Investigatory Powers Tribunal.[69] The UK also has an independent Intelligence Services Commissioner and Interception of Communications Commissioner, both of whom are former senior judges.[70]

The Investigatory Powers Tribunal ruled in December 2014 that GCHQ does not breach the European Convention of Human Rights, and that its activities are compliant with Articles 8 (right to privacy) and 10 (freedom of expression) of the European Convention of Human Rights.[66] However, the Tribunal stated in February 2015 that one particular aspect, the data-sharing arrangement that allowed UK Intelligence services to request data from the US surveillance programmes Prism and Upstream, had been in contravention of human rights law prior to this until two paragraphs of additional information, providing details about the procedures and safeguards, were disclosed to the public in December 2014.[71][72][73]

Furthermore, the IPT ruled that the legislative framework in the United Kingdom does not permit mass surveillance and that while GCHQ collects and analyses data in bulk, it does not practice mass surveillance.[66][74][75] This complements independent reports by the Interception of Communications Commissioner,[76] and a special report made by the Intelligence and Security Committee of Parliament; although several shortcomings and potential improvements to both oversight and the legislative framework were highlighted.[77]

4.7 Constitutional legal case

A controversial GCHQ case determined the scope of judicial review of prerogative powers (the Crown's residual powers under common law). This was *Council of Civil Service Unions v Minister for the Civil Service* [1985] AC 374 (often known simply as the "GCHQ case"). In this case, a prerogative Order in Council had been used by the prime minister (who is the Minister for the Civil Service) to ban trade union activities by civil servants working at GCHQ. This order was issued without consultation. The HouseofLordshadto decidewhetherthiswasreviewable by judicial review. It was held that executive action is not immune from judicial review simply because it uses powers derived from common law rather than statute (thus the prerogative is reviewable). Controversially, they also held that although the failure to consult was unfair, this was overridden by concerns of national security.

4.8 Leadership

Main article: Director of the Government Communications Headquarters

The following is a list of the heads of the operational heads of GCHQ and GC&CS:

- Alastair Denniston CMG CBE (1921 – February 1942) (continued as Deputy Director (Diplomatic and Commercial) until 1945).
- Sir Edward Travis KCMG CBE (February 1942 – 1952)
- Sir Eric Jones KCMG CB CBE (April 1952 – 1960)
- Sir Clive Loehnis KCMG (1960–1964)
- Sir Leonard Hooper KCMG CBE (1965–1973)
- Sir Arthur Bonsall KCMG CBE (1973–1978)
- Sir Brian John Maynard Tovey KCMG (1978–1983)
- Sir Peter Marychurch KCMG (1983–1989)
- Sir John Anthony Adye KCMG (1989–1996)
- Sir David Omand GCB (1996 –1997)
- Sir Kevin Tebbit KCB CMG (1998)
- Sir Francis Richards KCMG CVO DL (1998–2003)
- Sir David Pepper KCMG (2003–2008)
- Sir Iain Lobban KCMG CB (2008–2014)
- Robert Hannigan CMG (2014–present)

4.9 Stations and former stations

The following are the stations and former stations that continued to operate through the Cold War:[78]

- Current stations
- GCHQ Ascension Island
- GCHQ Bude
- GCHQ Scarborough
- Former stations
- GCHQ Brora
- GCHQ Cheadle
- GCHQ Culmhead
- GCHQ Hawklaw
- GCHQ Hong Kong

4.10 In popular culture

The historical drama *The Imitation Game* featured Benedict Cumberbatch portraying Alan Turing's efforts to break the Enigma code as part of the Government Code and Cypher School, the forerunner of GCHQ.[79]

4.11 See also

- Capenhurst
- Hugh Alexandeat GCHQ from 1949–1971r – head of the cryptanalysis division
- RAF Digby
- RAF Intelligence
- UK Cyber Security Community
- UKUSA Agreement
- Zircon, the cancelled GCHQ satellite project
- Operation Socialist
- Joint Operations Cell

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more intrusive measures that our security service and police have available to them – i.e. Intercept, intercepting people's telephones and some other intrusive measures – the decision is taken by the Secretary of State, predominantly me. A significant part of my job is looking at these warrants and signing these warrants. I think it's ... Some people argue that should be to judges....I think it's very important that actually those decisions are being taken by somebody who is democratically accountable to the public. I think that's an important part of our system. I think it's a strength of our system.

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4.14 External links

- Official website
- Her Majesty’s Government Communications Centre
- CESG
- GovCertUK
- GCHQ: Britain’s Most Secret Intelligence Agency
- BBC: A final look at GCHQ’s top secret Oakley sitin Cheltenham e
- INCENSER, or how NSA and GCHQ are tappininternet cables g

Coordinates: 51°53′58″N 2°07′28″W / 51.89944°N 2.12444°W

Chapter 5

Hut 8

Hut 8 was a section in the Government Code and Cypher School (GC&CS) at Bletchley Park (the British World War II codebreaking station) tasked with solving German naval (Kriegsmarine) Enigma messages. The section was ledinitiallybyAlanTuring. HewassucceededinNovember 1942 by his deputy, Hugh Alexander. Patrick Mahon succeeded Alexander in September 1944.[1]

Hut 8 was partnered with Hut 4, which handled the translation and intelligence analysis of the raw decrypts provided by Hut 8.

Located initially in one of the original single-story woodenhuts, thename“Hut8”wasretainedwhenHuts3, 6 & 8 moved to a new brick building, Block D, in February 1943.[2]

After 2005, the first Hut 8 was restored to its wartime condition, and it now houses the “HMS Petard Exhibition”.[3]

5.1 Operation

In 1940, a few breaks were made into the naval “Dolphin” code, but Luftwaffe messages were the first to be read in quantity.[4] The German navy had much tighter procedures, and the capture of code books was needed (see Battle of the Atlantic § Enigma) before they could be broken. In February 1942, the German navy introduced “Triton”, a version of Enigma with a fourth rotor for messages to and from Atlantic U-boats; these became unreadable for a period of ten months during a crucial period (see Enigma in 1942).

Britain produced modified bombes, but it was the success of the US Navy bombe that was the main source of reading messages from this version of Enigma for the rest of the war. Messages were sent to and from across the Atlantic by enciphered teleprinter links.

5.2 Personnel

In addition to the cryptanalysts, around 130 women worked in Hut 8 and provided essential clerical support including punching holes into the Banbury sheets. Hut 8 relied on Wrens to run the bombes housed elsewhere at
Bletchley.[1]

5.2.1 Code breakers

- Michael Arbuthnot Ashcroft[1]
- Joan Clarke [1]
- Harry Golombek
- I. J. Good
- Peter Hilton, January 1942 to late 1942
- Rosalind Hudson
- F Anthony Kendrick[1]
- Leslie Lambert (aka “A. J. Alan”)
- Patrick Mahon[1]
- Rolf Noskwith[1]
- Richard Pendered[1]
- Alan Turing
- Conel Hugh O'Donel Alexander
- Shaun Wylie[1]
- Leslie Yoxall devised Yoxallismus technique

5.3 See also

- Banburismus
- Hut 4
- Hut 6
- B-Dienst

- OP-20-G

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5.5 Text and image sources, contributors, and licenses

5.5.1 Text

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Hyad, Arado, Lincolnite, Hede2000, Splash, Chris Capoccia, Op. Deo, SluggoOne, SpuriousQ, Scott5834, Hydrargyrum, Gaius Cornelius,

CambridgeBayWeather, Rsrikanth05, KSchutte, DonaldDuck, Big Brother 1984, NawlinWiki, DavidConrad, Borbrav, Aeusoes1, Czyrko,

Trovatore, Rupert Clayton, Twin Bird, Gareth Jones, Howcheng, Ragesoss, Retired username, Vivenot, Bigpad, Jpbowen, Vancouveriensis, Scs, Tony1, Evmore, Syrthiss, DGJM, Gadget850, Bota47, Dv82matt, EAderhold, Capt Jim, Phgao, PTSE, Homagetocatalonia, Closedmouth, Rms125a@hotmail.com, Abune, JRawle, Vdgr, Alias Flood, Eric Guez, Mais oui!, Garion96, Bpmsmith, Calilasseia, Eaefremov, Tarquin Binary, Kungfuadam, Habbie, Radi0head, NeilN, Rwwww, GrinBot~enwiki, Roger wilco, Jimerb, Tom Morris, Bibliomaniac15, TechBear, Chris Chittleborough, KnightRider~enwiki, Damson88, SmackBot, Pjthompso, Mmernex, Bobet, Nihonjoe, InverseHypercube, Duvel, McGeddon, Bomac, KocjoBot~enwiki, Zzzzz, Jfgrcar, Delldot, ZerodEgo, Kintetsubuffalo, Canderra, RyanSKing, Yamaguchi , Maarten1963, Peter Isotalo, Gilliam, Skizzik, Icemuon, Chris the speller, Fintler, RDBrown, Achmelvic, MalafayaBot, Psycho 79, Kungming2, Spellchecker, DHN-bot~enwiki, Zephyrad, Rlevse, D-Rock, Scwlong, Modest Genius, Mike hayes, Tsca.bot, Can't sleep, clown will eat me, MisterHand, Allemannster, OrphanBot, Rrburke, Lesnail, Flubbit, Kcordina, Lobner, SanderK, Anas hashmi, Harnad, Stevenmitchell, Crboyer, Aldaron, Fuhghettaboutit, Robert A Shapiro, Cybercobra, Bigturtle, Nakon, T-borg, VegaDark, RJN, Tompsci, Ggpauly, StephenReed, Adrigon, Wuzzy, Hammer1980, DMacks, Quatloo, Bdiscoe, Marcus Brute, Risker, Curly Turkey, Davidtheconqueror, Andrei Stroe, Andrew Dalby, Gregapan, Ohconfucius, Michael David, SashatoBot, Lambiam, Doug Bell, Ser Amantio di Nicolao, Kuru, John, Pliny, Mathiasrex, Kipala, Books++, Swellesley, Evenios, This user has left wikipedia, Kashmiri, IronGargoyle, Filippowiki, The Man in Question, Slakr, Noah Salzman, Mr Stephen, Optakeover, Ryulong, MTSbot~enwiki, Skinsmoke, LaMenta3, Dl2000, Asyndeton, Hu12, Norm mit, BranStark, Rizwanadil, Iridescent, Hayttom, Mwhite66, JoeBot, JHP, Sam Clark, Beno1000, Richard75,

Courcelles, Nuttyskin, Academe, Coreycubed, Chris55, Danrook, Kotepho, Anthony22, Scohoust, Saltation, Drinibot, Tschel, Jnicho02, Stevo1000, Jcoffland, N2e, Hakkasberra, Location, Mike 7, Gregbard, Guy Chisholm, Draken251, Yaris678, Cydebot, Wikien2009, Maria

Vargas, Brit tit45, Reywas92, Slp1, Treybien, UncleBubba, Gogo Dodo, Vladimir Drzik, Corpx, Otto4711, Agne27, Trident13, Dean Morrison, Moxmalin, Moleware, DumbBOT, Nabokov, ErnstRohlicek, EqualRights, Chris Henniker, Garik, ErrantX, Bflood, Omicronpersei8, Richhoncho, PKT, Trueblood, Michael Fourman, Malleus Fatuorum, Jon C., Thijs!bot, Epbr123, Biruitorul, Captain Pedant, Coelacan, Chitomcgee, Daniel, Ruchi29383, Jd2718, N5iln, Edwardx, Sopranosmob781, Headbomb, Fluxbot, Marek69, Iozeren, Electron9, Ufwuct, Lewallen, X201, Tellyaddict, Hjoab, Benqish, J. W. Love, AntiVandalBot, RobotG, Changlinn, MrMarmite, Majorly, Saimhe, Yonmei, Masamage, Pmt6sbc, Readro, 17Drew, Julia Rossi, Tjmayerinsf, Mack2, Whoosher, Dylan Lake, Danger, Axxaer,

NJW494, Res2216firestar, Deadbeef, Bigjimr, JAnDbot, Tigga, Deflective, Barek, MER-C, Skomorokh, AP.BOT, Caracaskid, Noble Korhedron, Stellmach, Michaelarabin, Ericoides, Samuel Webster, Vivliothykarios, Stonnman, Albany NY, Awien, Leolaursen, TAnthony, Bzuk, PhilKnight, Rothorpe, Psicorps, Hugh.glaser, Wildhartlivie, Freshacconci, Magioladitis, Connormah, WolfmanSF, Bongwarrior, VoABot II, Xb2u7Zjzc32, JamesBWatson, Jay Gatsby, Ling.Nut, Alsavage, RobTheGob, BjörnF~enwiki, Soulbot, Waacstats, Cathalcom, Cic, Schily, Aero2~enwiki, Emanuele Saiu~enwiki, Bleeter, KConWiki, Fabrictramp, Theroadislong, Lenschulwitz, Shocking

Blue, MetsBot, Allstarecho, David Eppstein, $yD!, GeoFan49, Enquire, DerHexer, JaGa, Smartings, Xlboy~enwiki, Olsonist, Goldsztajn,

MichaelGood, Aleksej00, MartinBot, Church of emacs, BetBot~enwiki, Alexswilliams, Poeloq, Timothy Titus, Nikdog, Garciala1, Keith

D, MChalk, CommonsDelinker, Ramesh Chandra, Fordescort79, Simonsays440, JBC3, Slash, Deben Dave, Paranomia, J.delanoy, Nev1,

Schmatt, DrKay, SuperGirl, Wa3frp, Rhinestone K, MistyMorn, Harkmopwood, Gretagolding, Stinkpete, Hair Commodore, EthicsGradi-

ent, It Is Me Here, PedEye1, Tai kit, Mccajor, LordAnubisBOT, Timuche, Ovidiu pos, Cen2s2s, Chriswiki, Robertson-Glasgow, HiLo48, Plasticup, Chiswick Chap, Pidara, Joel on the SOL, Nwbeeson, Rwessel, Hennessey, Patrick, 83d40m, Ontarioboy, Sunderland06, Rob Round, KylieTastic, Juliancolton, Homer Landskirty, Xyl 54, Vanished user 39948282, FrankEldonDixon, Ja 62, Varnent, Scewing, Patraiz, Sosayso, Spellcast, Jtyler111, Hugo999, Deor, Shiggity, Typhoner~enwiki, Derekbd, Pleasantville, AlnoktaBOT, Piggly, Lanapopp, Barneca, Mcewan, Philip Trueman, Martinevans123, TXiKiBoT, Oshwah, Silvestris, Zidonuke, Jere123 9, Technopat, Hqb, Spottedfire, GDonato, Magnius, Combatentropy, Djkrajnik, Sintaku, Martin451, TedColes, JhsBot, Voiceofreason01, MrASingh,

Nzrouillard, Duncan.Hull, Mkw813, Katimawan2005, Jmath666, Nedrutland, Mwilso24, Eubulides, Derfboy, Andy Dingley, Wolfrock, Synthebot, Falcon8765, VanishedUserABC, Softlavender, Cwmacdougall, Joelhowells, Alcmaeonid, Truthanado, HiDrNick, Symane, Jonathan.ian.ellis, Edofedinburgh, W4chris, Kafkasmurat, Katzmik, Austriacus, Hellow4, GirasoleDE, SieBot, Maher-shalal-hashbaz, Waldhorn, Nihil novi, Swliv, WereSpielChequers, Malcolmxl5, Jauerback, Alex Middleton, MarkBolton, Yintan, Calabraxthis, Bamkin, Jricken, Markdask, Bentogoa, Toddst1, Curuxz, Flyer22 Reborn, A. Carty, Arbor to SJ, SPACKlick, Clearwater2, Antonio Lopez, Baseball Bugs, PhilMacD, Omshivaprakash, ViennaUK, Lightmouse, SimonTrew, Ks0stm, Int21h, Afernand74, Kumioko (renamed), Werldwayd, Svick, Brudra, Maelgwnbot, CharlesGillingham, StaticGull, Thetwoms, Randomblue, Dabomb87, Joshschr, Kettlesart, 00vicky00, Tegrenath, Daddy-
Warlock, Budhen, ImageRemovalBot, Jacob Myers, Invertzoo, Martarius, ClueBot, Jay7779, Bob1960evens, Boodlesthecat, DFRussia, George norfolk, Billwilson5060, The Thing That Should Not Be, All Hallow's Wraith, Rodhullandemu, Audacitor, Eusebius, Kamath.nakul, JuPitEer, Arakunem, Gregcaletta, Ivesiana, Drmies, DownUndr, Bradka, Uncle Milty, Citizenkant, Richerman, LizardJr8, Schpinbo, Ottawahitech, Trivialist, Auntof6, Grandpallama, Pointillist, Sv1xv, Southdevonian, Ktr101, Greenmatter, Alexbot, Socrates2008, Eeekster, Baseballbaker23, Leonard^Bloom, Gwguffey, Rhododendrites, Helenginn, Holothurion, Dekisugi, 6afraidof7, Eastcote, Thehomesickalien, Chaosdruid, Midgetnat, JDPhD, Qwfp, Johnuniq, Iamaleopard, DumZiBoT, Wednesday Next, XLinkBot, MessinaRagazza, BodhisattvaBot, Imagine Reason, Vanished 45kd09la13, VTRAINMAN99, Chucheng, Section6, Avoided, Jprw, ManchesterMike2008, PaulBoxley, Arithmeticon, Good Olfactory, Zephyr32, Bridgetfox, Ajahewitt, WasabiJones, RyanCross, Addbot, C6541, AVand, Sockyboy, DOI bot, HARRZ, Nortonius, Ben Sarbey, TheUnknownCitizen, Blethering Scot, Ronhjones, Fieldday-sunday, Aboctok, Vishnava, Sillyfolkboy, Philbutt, AndersBot, MoreUnlikelyExplanations, Dr. Universe, Favonian, Torla42, Mad scientist03, LemmeyBOT, West.andrew.g, Lemonade100, ManymerrymenmakingmuchmoneyinthemonthofMay, Partofwhole, Brian Laishes, 84user, Numbo3-bot,
Alanscottwalker, Rcbryan, Lightbot, Krano, Jarble, Kroolik, Ben Ben, Pointer1, Luckas-bot, Yobot, EchetusXe, JJARichardson, Ybgay4, Hohenloh, Legobot II, Rsquire3, Donfbreed, Pcap, Darx9url, AllanPorvic, Washburnmav, Barroncx, AnakngAraw, DrFleischman, Mad artist, TheBigJagielka, Bbb23, Synchronism, ZapThunderstrike, AnomieBOT, Wikiyakapoola, DoctorJoeE, Arjun G. Menon, Rubinbot, 1exec1, Jim1138, Galoubet, JackieBot, Piano non troppo, Materialscientist, Melikbilge, Cyan22, DAFMM, Citation bot, James500, Carlsotr, Tsuguya, Frankenpuppy, ArthurBot, B. Fairbairn, Nifky?, Wikisilki, Xqbot, Melmann, Twentysixpurple, Wperdue, Millahnna, Hoping To Help, Mlpearc, Gap9551, Miym, GrouchoBot, Mechla, Rustygecko, Nittram, Alumnum, Andyhargreaves, Mark Schierbecker, RibotBOT, The Interior, Fredhater11, Flying Stag, Headhitter, Lindommer, Sheeson, GhalyBot, Nietzsche 2, Foxie001, Erik9, Captainn00dle, FreeKnowledgeCreator, Bogdantri, McAnt, FrescoBot, Tanynep, Jajhall, Pianone, Alxeedo, Cosmo Notch, Tommy wheel, Girlwithgreeneyes, Machine Elf 1735, Dagme, Cannolis, Jun Nijo, Jakesyl, Nonexyst, Citation bot 1, Redrose64, Yankhill, Hartiboozer, Scootercatter, Kiefer.Wolfowitz, Oliver81, Robert A. Maxwell, Skyerise, Moonraker, Jorgicio, Serols, SFRod, Theindiedave, ElNuevoEinstein, Beao, Crusoe8181, SkyMachine, Roseohioresident, Lightlowemon, FoxBot, Indexme, Trappist the monk, SchreyP, Biohazard35, Comnenus, Fox Wilson, Sci99, Teknad, Shisir 1945, Dinamik-bot, EdFalzer, Oracleofottawa, Vrenator, Cdnpacker, SeoMac, Bluefist,
AmyzzXX, Rorre resu, BobSilverman, SjoerdFerwerda, AtomicArab, Yondonjamts, TheMesquito, Jesse V., Mean as custard, Misscuty, Axxxion, RjwilmsiBot, DexDor, Dlambe3, Accosta2, Kvasilev, Regancy42, Bossanoven, Fappah, Javache, 42and5, WildBot, Aaron-
Townsend, Saint.Halls, Rollins83, DASHBot, Steve03Mills, Meesher, EmausBot, Orphan Wiki, WikitanvirBot, Immunize, BillyPreset, GoingBatty, RA0808, Austin Luft, Hounder4, Are You The Cow Of Pain?, Jim Michael, Winner 42, Wikipelli, K6ka, MikeyMouse10, Italia2006, Layik, AvicBot, Kkm010, John Cline, Checkingfax, Fæ, Érico, Wackywace, GianoM, Jonpatterns, JJGeneral1, Rsshelas, Kiwi-
Jeff, A930913, James Flux, Winchester43, H3llBot, Quondum, Hydriz, K kisses, Unreal7, AManWithNoPlan, Wikignome0530, Fintflint, Wingman4l7, Bullmoosebell, Brandmeister, Boatgypsy, Danmuz, Donner60, Caylane, Tfenglish, Neutral bias, HandsomeFella, MU1824, Laurapalmerr, Igs1963, BabbaQ, FeatherPluma, Rocketrod1960, Potasmic, Mjbmrbot, Sonicyouth86, ClueBot NG, Bourbaki78, Jackminardi, SusikMkr, Nivektrah, Hon-3s-T, David O. Johnson, Gef05, Neljack, Marcus Paul, Widr, Neoprometheus, Oxford73, CerebrumMor,htimSefaL,mut ساجد امجد ساجد, Jrobin08, Helpful Pixie Bot, Pjefts, Gliere, Babulbaishya, Gob Lofa, Bibcode Bot, BG19bot, Gael13011, MKar, PearlSt82, Cyberpower678, Fromthehill, MusikAnimal, Geraldo Perez, Allecher, Mark Arsten, FutureTrillionaire, Pclv888822, Scientiom, Jacobns, KiwiRyan, MrBill3, Ds10world, Grgizem, Leo168haha, SemtexUXB, Glacialfox, Bluffalobrill, Rimianika, Yeskarthik, Drianwatson, Fylbecatulous, JGMachen, Marcokrt, Fuse809, BattyBot, Justincheng12345-bot, Tutelary, Solntsa90, Kbp3, RichardMills65,
Vanished user lt94ma34le12, Bruderer~enwiki, Stausifr, Cloptonson, Ninmacer20, Cyberbot II, Chie one, ChrisGualtieri, HiNatasha, Ozzyiommi, Andrew.john.phillipson, Jethro B, Soulparadox, Thom2729, XsHoa10pSogRcAVgjAxsVMs1C1BbYUspRh, Giso6150, JYBot, Mitchell NZ, Asisman, Laggan Boy, Dexbot, Zeeyanwiki, Op4ev, Reverend Mick man34, Jonny Nixon, Mogism, RosscoEdinburgh, Emurrayc, Pluto and Beyond, Cerabot~enwiki, Etsg123, Garrett579246, Sanguninemybrother, Axei18, Noczesc, Color2were, Mehditations, Hal Mangen, Periglio, Fairyspit, VIAFbot, Frosty, Zach H77, Blackredstart, Johnxsmith, Athomeinkobe, BTRand1, Malerooster, Gregallmighty, Lomicmenes, Epicgenius, TheManTroll, Peameal Bacon, HKH28, Pondical, JamesDLankin, Kp1983, Melonkelon, Alexandre Candalaft, Ayub407, Srwaxm, Paigdeck, Ikewade, Mphenley, Snhought, Satassi, Abhisatya, Mcioffi, Rachelhjaffe, Alexakh, Nowakh, Amykam32, Nbak, Alepisto, Maeganm, Mldisch, Slodomat, Erviale, Haeisen, Lukesimo, Kkhorfan, Cleeho, Azkle, Hiray91, Jakec,
Lemaroto, RaphaelQS, Mathmensch, Babitaarora, Superblake, Artismyhammer, Grapestomper9, Zenibus, 3reretrt, NottNott, Mandruss, Ginsuloft, JeanLucMargot, Japanesehelper, Abaroness, Erudite Manatee, Airwoz, SOLIDSNAKE1234, JaconaFrere, 32RB17, Ritestuff, Jonjon889933, Undeadherbs, MadScientistX11, Bilorv, WackyPhysicist, Trac43, Captain Cornwall, MCarsten, Ianfox123, Destan123, Lasonia, Orbitrack~enwiki, Parabolooidal, Monkbot, Ohdwalter, Raghupon, Stenskjaer, Tobermory Womble, Filedelinkerbot, Xchrisdx, AntiqueReader, Pieter202, Jjaysmith63, Jubjub123456789, Trosham, Equilibrium103, Warycary, Fireheart10, HertsChorus, Johnsoniensis, Hertsman, SherborneArchives, Jonarnold1985, Vanisheduser00348374562342, Mark S Ormesher, HMSLavender, Emotasticemu, LowLightImages, Ukcorwalch, ChamithN, Brightnsalty, Philipnelson99, Imagikatrix, Majorgrammarfreak, AlanTuringFan, YeOldeGentleman, Strongjam, Jaqueline32, Alexwood21, Richtea321, Babylove0306, DiscantX, Dietic, Violetteplessz, Joseph2302, Phantom gamer 1993, JCdaboss, Mannykant, KasparBot, Tingtong1234567890, JorisEnter, Elliotpieri7, Mgoyal69, KSFT, PurpleGuyyy, SSTflyer, MamaFakerPro, AquaFINA101, ProboscideaRubber15, ALANETWORK, TheArtMaster808, 89sec, Firoznavas, Tabbieforbes, Foamfanaticlloyd, Bobbobblaw, Awesome kid 0429, Fyyydrfymigudtswaq, Ssssjsjs, Smexy1tardis, 17Mercury37 and Anonymous: 1360

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