Contextualizing Colossus: Codebreaking Technology and Institutional Capabilities

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Abstract:

The Bletchley Park codebreaking center sits close to the heart of Britain's collective sense of historical greatness. Historians view it as a highly successful but largely ad-hoc institutional response to novel cryptographic challenges, depicting both its reliance on elite mathematicians and a large labor force as ruptures with peacetime practice. In contrast, we suggest that underpinning Bletchley Park's success were institutional capabilities established in the pre-war British state. We focus on the celebrated "Colossus" electronic codebreaking devices as one element of a highly successful institutional collaboration between Bletchley Park, where they were used, and the Post Office research station at Dollis Hill where they were designed and built. We reveal the development of a productive institutional partnership sponsored at the highest levels of government and supported by managers on both sides, correcting claims that Post Office engineer Tommy Flowers built the first machine at his own expense without the support or knowledge of Bletchley Park's managers.

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In 1940 Winston Churchill promised that the forthcoming Battle of Britain would, a thousand years later, still be remembered as the British Empire's "finest hour." Eighty of these years have now passed and, despite the rapid collapse of said empire, the battle looms larger than ever in the nation's collective memory.

Yet Britain's understanding of that struggle has changed fundamentally. Churchill himself spoke of a shared struggle involving teamwork and sacrifice. Millions of members of the armed forces were, as David Edgerton has shown, supported by a powerful industrial base and national mobilization coordinated by experts of all kinds.[1] Since then the nation has grown to distrust institutions, experts, military commanders, manufacturing industries, and state planning. In its imagination the site of victory has progressively shifted away from battlefields, factories, and international alliances, towards Bletchley Park: the center of Britain's formidable and once secret codebreaking effort. It was mathematical and technological innovation that won the war, not mass mobilization or armed struggle.

The Oscar-winning 2014 movie *The Imitation Game* applied the narrative structure and beats of a superhero movie to Bletchley Park: an autistic Alan Turing introduces himself as "the best mathematician in the world," dismisses the aid of Britain's brightest ("these men would only slow me down"), and builds a war-winning computer. Bletchley Park's idiotic military commander enters the frame only to try to order Turing arrested and his machine smashed. Five codebreakers secretly run the Battle of the Atlantic from their machine room. Having outwitted the armed forces of both Germany and Britain, Turing defines the main difference between him and the Almighty: "God didn't win the war." Silly as it was, the film differed more in degree than in kind from other narratives of innovation at Bletchley Park. Bletchley Park has been turned into a kind of prototype for Silicon Valley, itself misunderstood in popular accounts (such as the work of Walter Isaacson) as the creation of a handful of genius hackers.[2]

This article re-evaluates Bletchley Park's technological triumphs, focusing on the Lorenz teleprinter cipher known to the British as "Tunny" rather than the Engima work with which Turing was associated.[3] The effort to break Tunny is often claimed to have had a more significant impact on the war's progress. It produced the Colossus machines, large digital electronic devices often, if tendentiously, remembered as the first programmable electronic computers.[4] They have been celebrated in books, television programs, and a recent special issue stamp.

Though Turing had little to do with Colossus, the same narrative template of the lone genius battling short-sighted bureaucrats underpins most retellings of the Colossus story. These cast telecommunications engineer Tommy Flowers as the genius. Flowers develops Colossus despite Bletchley Park managers dismissing his visionary faith in electronics. He incurs hefty

[1] David Edgerton, *Britain's War Machine*.

[2] Walter Isaacson, *The Innovators*.

[3] Roberts, *Lorenz: Breaking Hitler's Top Secret Code at Bletchley Park*.

[4] Haigh and Priestley, "Colossus and Programmability."

personal debts to buy components, before unexpectedly delivering the machine to codebreakers dumbfounded by its capabilities.

This narrative crumbles under closer investigation. Our aim here is not to quibble with the detail of existing accounts but to challenge broader assumptions undergirding the established narrative of Colossus. The real story is as much one of engineering, procurement, and logistics, as of mathematical accomplishment. We treat the introduction of Colossus as a process spanning many months of tinkering, repair, and the development of new procedures rather than as a single abrupt passage from pre-electronic to electronic. We focus on institutional capabilities rather than individual genius, on continuities rather than technological ruptures between Colossus and other codebreaking machines. Most fundamentally, we broaden the institutional story by treating the Colossus machines as being as much a part of the history of the Post Office Research Station at Dollis Hill, where they were designed and built, as of Bletchley Park.

We are not, of course, the first historians to look at the broader context of Bletchley Park. Historian Jon Agar, looking at the huge scale of the Enigma effort, depicted a modern, technocratic organization overseeing an efficient decryption production line in accordance with established civil service procedures. Historian Christopher Smith and organizational scholar Christopher Gray have separately studied the management and organization of Bletchley Park.[5] They suggested a more complex picture: "professional and mechanical in some areas but unorthodox, unregimented and, perhaps, even anarchic in others, particularly those deemed to require leeway" for creativity.[6] Oral and social histories, highlighting the experience of the thousands of ordinary people who worked at Bletchley Park confirmed this heterogeneity.[7]

Our distinctive contribution is to bring these institutional perspectives to the story of Colossus. We situate our account against three of the most influential, comprehensive, and detailed historical accounts its development. Brian Randell, a computer scientist and pioneering computer historian, interviewed many participants when their memories were fresh but written material was still classified. His groundbreaking description of Colossus was published in 1980.[8] Journalist Paul Gannon published the outstanding book-length treatment *Colossus: Bletchley*

[5] Grey, *Decoding Organization: Bletchley Park, Codebreaking and Organization Studies*; Smith, *The Hidden History of Bletchley Park: A Social and Organizational History, 1939-45*.

[6] Smith, "How I Learned to Stop Worrying and Love the Bombe," 204.

[7] For a comprehensive oral history, see McKay, *The Secret Lives of the Codebreakers*. Other histories focused on particular social or occupational groups, such as Smith, *The Debs of Bletchley Park and Other Stories*; McKay, *The Secret Listeners: How the Y Service Intercepted the German Codes for Bletchley Park*. They have been supplemented by a sizable body of memoir, such as Welchman, *The Hut Six Story: Breaking the Enigma Codes*; Briggs, *Secret Days: Codebreaking in Bletchley Park*; Russell-Jones and Russell-Jones, *My Secret Life in Hut Six: One Woman's Experiences at Bletchley Park*.

[8] Randell, "The Colossus." An earlier version, circulated in 1976, first brought Colossus to public attention. Williams, "The First Public Discussion of the Secret Colossus Project."

Park's Greatest Secret in 2006, drawing on a mass of newly declassified archival material.[9] Philosopher Jack Copeland, an active chronicler of all things Turing, edited *Colossus*, a compendium of reminiscences, technical analysis, and historical narrative.[10]

Dollis Hill, Meet Bletchley Park

In an outlying north-west London community stood a monumental building with "Research is the Door to Tomorrow" carved into its large portico. Beyond, at the main door, was "To Strive, To Seek, To Find."[11] Usually called "Dollis Hill," it housed the top engineering talent of the General Post Office. This postal service also ran Britain's telephone system and globe-spanning imperial telegraph network. When World War II broke out, Flowers headed the largest research and development team at Dollis Hill, the Switching Group, with about fifty staff, ten of them professional engineers.[12] They led one of Dollis Hill's most conspicuous accomplishments of the 1930s: automated local exchanges, with electromechanical switches making connections under the control of digital pulses. Dollis Hill was also a center of expertise in electronics. Long distance telephony relied on high performance electronic amplifiers. They were analog: changes in the volume of the audio picked up by the handset were transmitted as proportional changes in the current flowing along telephone wires. Even before the war, Flowers' team had been experimenting with integrating electronics into switching processes, to support the long-distance transmission of dialing control information. Colossus, like a digital computer, conjoined these telephonic practices: electronic like the amplifiers, digital like the automatic switches. Colossus also depended on digital information stored on paper tape—a technique used with teleprinters but not with telephones.

We believe that Dollis Hill and Bletchley Park first worked together to tackle the Enigma cipher—Germany's main method of protecting its radio communication with submarines, boats, and remote airfields. Bletchley Park's codebreakers frequently broke Enigma from 1940 onward. Enigma machine settings changed daily. Discovering them required intense and skilled labor, aided by many "bombes." These electro-mechanical devices, conceived by Turing and Gordon Welchman building on Polish ideas, were designed and manufactured by the British Tabulating Machine Company (BTM) under chief engineer, Harold "Doc" Keen.[13] This collaboration set a template for Bletchley Park's later relationship with the Post Office as an external source of technical expertise and manufacturing capabilities.

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[9] Gannon, *Colossus*.

[10] Copeland, *Colossus*. He later offered his own version of the Colossus story in Copeland, *Turing*, ch 7.

[11] Thanks to Mark J Crowley for bringing the inscriptions to our attention (he attributes them to British Library Sound Archive, C1379/28 Interview with Stephanie Shirley).

[12] Randell, "The Colossus."

[13] BTM had a license from what became IBM to develop punched card technology for sale throughout the British Empire. Campbell-Kelly, *ICL*, 118.

The first prototype arrived in May 1940. Turing reportedly boasted at the time that "with 10 machines he could be sure of breaking Enigma and keeping it broken."[14] It took many more: thousands of workers and hundreds of machines. Even this codebreaking factory could not keep Enigma broken after Germany added a fourth encoding rotor to its Naval Enigma machines in January 1942. That allowed for many more possible encryption settings, increasing by a factor of about fifty the work required to identify the correct ones. By March, Bletchley Park had enlisted Flowers and his group to create a "stop testing" device intended to automate an aspect of the task previously left to human operators.[15]

This was just one of several technologies being tested in a bid to shift the advantage back towards the codebreakers. Since late 1941, Bletchley Park had been working with physicist Charles E. Wynn-Williams, who spent the war working for the Telecommunications Research Establishment (TRE), the center of Britain's radar research and development. Wynn-Williams specified the addition to the bombes of a device soon nicknamed "Cobra" because of the shape of a huge cable used to connect a new drum rotating 3,000 times every minute, three times faster than the fastest parts of the existing bombes. Spinning faster let the bombe evaluate more possible Enigma settings each minute. Wynn-Williams believed that relay technology, used in BTM's punched card machines and bombes, could never work quickly enough to extract information from the new drum. Gordon Welchman, who ran Bletchley Park's largest Enigma group, considered him "one of the leading experts on high speed work with valves" (the British name for the electronic components which Americans called "vacuum tubes").[16] He designed an electronic "sensing unit" to be used with Cobra, inspired by his pioneering prewar use of electronic counters for particle physics.

Christopher Smith and Paul Gannon have documented the tense relationships between Keen (BTM), Flowers (Post Office), and Wynn-Williams (TRE).[17] Nothing went as planned. Wynn-Williams' prototype electronic sensing unit, promised by the end of May 1942, was late.[18] Cobra production by Mawdsley, a commercial engineering firm, also foundered.

Dollis Hill's involvement with the bombe work deepened when William W. Chandler, a member of Flowers' group, was assigned to help Wynn-Williams with electronic sensing.[19] Dollis Hill was also charged with getting the Post Office to manufacture 72 copies once the design was finalized.[20] When Wynn-William's prototype finally arrived from TRE the Dollis Hill engineers judged it unworkable. Flowers began promoting his own alternative design.

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[14] Frank Birch, letter to Travis quoted in Mahon, A P. *The History of Hut Eight, 1939-1945*, HW 25/2 at the British National Archives (hereafter TNA).

[15] C.S.S. Memorandum, 16 March 1942, HW 62/4, TNA.

[16] Welchman to A.D.(S) (de Grey), 4 June 1943, HW 62/5, TNA.

[17] Smith, "How I Learned to Stop Worrying and Love the Bombe"; Gannon, *Colossus*, 247-253.

[18] Meeting Held at Bletchley Park on 12 May 1942, HW 62/4, TNA

[19] Andrew Hodges, *Alan Turing*, 286.

[20] Radley to Travis, 2 March 2, 1943, HW 62/5, TNA.

Welchman later claimed that by the "the end of September 1942" he was already "very seriously worried" that Cobra would never work.[21] Without a functioning Cobra prototype the rival sensing units could not be tested. The dispute dragged on, inconclusively, for months.

Early Work on Tunny

By the time Flowers' dispute with Wynn-Williams reached its peak in the summer of 1943 both men were deeply engaged with the separate project that eventually produced Colossus. For its highest-level military communications, Germany relied not on Enigma but on teleprinters with attachments built by Lorenz to automatically encrypt messages while typed and decrypt them when received. Army command centers in France, Eastern Europe, the Balkans, and Scandinavia were beyond the central European wired network, forcing reliance on radio links and advanced encryption. German teleprinter operators called the radio attachments to their machines "Sägefisch" (sawfish).[22] After discovering the term in intercepted transmissions, the British termed the entire wireless teleprinter network "Fish" and codenamed individual links, such as "Sturgeon" and "Jellyfish," after aquatic fauna.[23]

Lorenz-encoded messages were first identified in 1941 on a link between Berlin and Athens known to the British as "Tunny" (a variant on "tuna"). Tunny was retained as a code name for the cipher itself and for material encoded with it.[24] Bletchley Park's small Research Section experimented on cracking it. Without ever seeing a Lorenz machine, mathematician Bill Tutte and career Army cryptologist John Tiltman managed to isolate a long passage of cipher key and reverse engineer the structure of the device producing it.[25]

Duplicating the Lorenz machine was an intellectual triumph, yet did not suffice to read the encrypted messages. The circumference of each of twelve cipher wheels inside the device was covered with tiny pins that could be pushed in or left up. To decrypt a message, you had to know the pin patterns used to encode it. Most wheel settings were originally changed infrequently, remining useful for weeks once broken, but by the end of the war the Germans were changing them all daily. Finding the pin settings was "wheel breaking." You also had to know the start positions for each wheel, which changed with each message sent. Determining them was known as "wheel setting."

[21] Welchman to A.D.(S) (de Grey), 4 June 1943, HW 62/5, TNA.

[22] According to Frode Weierud, "Bletchley Park's Sturgeon" the name "was derived from the sawfish-like shape of the signal" displayed on the radio receivers.

[23] "Non-Morse (Teleprinter) Transmissions – Saegefish," 3 May 1942, HW 14/36, TNA.

[24] D.D.(S). (Travis), untitled memo, 10 May 1942, HW 14/36, TNA.

[25] This is an often told story, notably by in Tutte, "My Work at Bletchley Park."

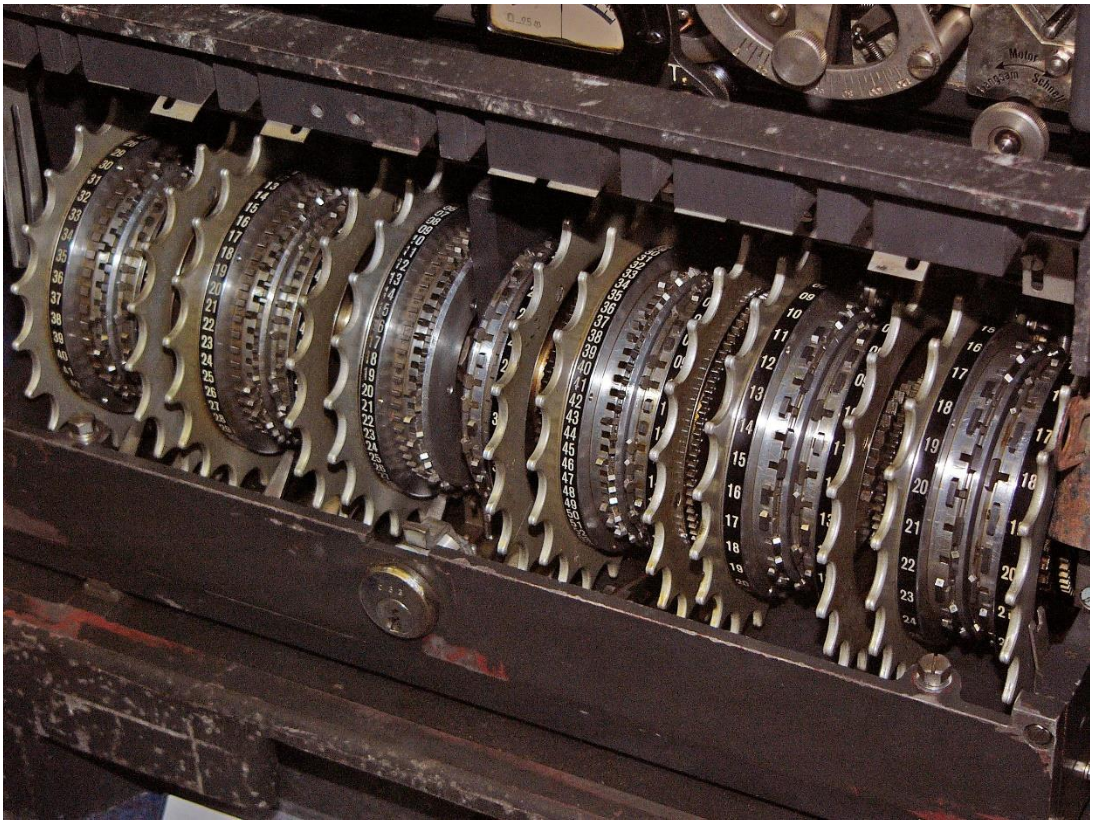

Figure 1: The code wheels of this Lorenz cipher unit, used to encrypt high-level German military messages for radio transmission, rotated as each character was typed on the attached teleprinter. The cipher was called "Tunny" by the British. Decrypting an intercepted message required both the pattern of raised and lowered pins on each wheel ("wheel breaking") and the start positions used for the individual message ("wheel setting"). (Source: Matt Crypto).

A new station at Knockholt intercepted and cleaned up the encrypted messages. By July codebreaking techniques were working well enough to establish a Bletchley Park section to decrypt Lorenz-encoded messages. Its initial successes relied on German operators' errors and lax security. Until November 1942, operators transmitted unencrypted indicators for wheel settings at the start of each message. As a result, "decodes were being produced, when [wheel patterns for] a month had been broken, a very few hours after interception."[26]

Mechanizing the Attack on Tunny

In November, 1942, the Germans replaced the Tunny radio link with new links using the same cipher but implementing tighter security procedures. The wheel settings indicators relied on by codebreakers were no longer included in each message. Bletchley Park's response was to mechanize parts of the codebreaking process. Within weeks of the German innovation Tutte came up with a new method for wheel setting that did not rely on luck or security lapses. Executing it required no mathematics more complex than counting but was far too laborious to

[26] "History of the Fish Sub-Section of the German Military Section, June 1942-May 1945," HW 50/63, TNA.

be done routinely by hand. The biggest challenge in decoding a message was setting a group of five cipher wheels, dubbed the “Chi wheels,” which could take 22 million possible combinations. Setting the first two wheels using Tutte’s method required 1,271 passes through several thousand characters of encrypted text. Each pass tallied coincidences between the message text and the output of cipher wheels when started in a specific pair of positions. The highest scores indicated the likeliest wheel settings.[27] Similar processes then set the other three wheels. Here, as in factories, mechanization was made possible by the routinization of work.

Cipher wheel output and message text both had to be represented in some medium that could be interpreted by a counting machine. Early discussions considered various approaches including sliding photographic films over optical sensors.[28] The effort was led by distinguished Cambridge University mathematician Max Newman, who was officially asked to “centralize research on special machinery” for codebreaking, effective February 1, 1943.[29] His group was known as “the Newmanry,” while the existing Tunny group, headed by Ralph Tester, became the “Testery.” The Newmanry was initially tiny compared with the legions working on Enigma: “one cryptographer, two engineers, and 16 Wrens [members of the Women’s Royal Naval Service].”[30]

To procure his “special machinery” Newman worked within, not against, existing bureaucratic alliances. His approach, probably chosen in consultation with Wynn-Williams, used looped paper tapes to hold the intercepted message and code wheel sequences. The tape mechanisms were assigned to Dollis Hill where the Telegraph Group, headed by F.O. Morell, had expertise in using paper tape to store and process messages.[31] Dollis Hill was also responsible for building, to Wynn-Williams’ design, plug boards and logic circuits to select and combine the signals read from tape. Their output would be tallied in partially electronic counters designed and prototyped by Wynn-Williams at TRE.[32]

The government supported this mechanization program. In February, Churchill’s chief military advisor Major General Hastings Ismay, issued Stanley Angwin, the Post Office’s engineer-in-chief, with a note on behalf of the Chiefs of Staff authorizing “every facility in the

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[27] One of us attempted a short explanation of this process in Thomas Haigh, “Colossal Genius: Tutte, Flowers, and a Bad Imitation of Turing.”

[28] Travis to Tiltman, 26 December 1942, HW 14/62, TNA.

[29] D.D.S. (Travis), “D.D.(S) Serial Order No. 80,” HW 14/66, TNA.

[30] James A. Reeds, Whitfield Diffie, and J.V. Field, *Breaking Teleprinter Ciphers*, 262-3, sect. 31B, is an annotated edition of the 1945 “General Report on Tunny” generally attributed to I. Jack Good, Donald Michie, and George Timms. Citations list both the pages for the book and section numbers usable with online versions of the report.

[31] Randell, “The Colossus,” 61.

[32] According to Reeds, Diffie, and Field, *Breaking Teleprinter Ciphers*, 39, sect. 15A the prototype machine was “commissioned” in January, 1943.

way of staff and materials" needed to mechanize the breaking of Tunny.[33] That largess contrasted with the general wartime squeeze on Post Office resources, including the conscription of 8,500 of its 42,000 engineers.[34]

Gordon Radley, the director of Dollis Hill, was nevertheless concerned about the new commitment. He asked Nigel de Grey, Bletchley Park's deputy director, to help ensure that subcontractors and suppliers, such as the Inter Service Components Committee and the Radio Board, prioritized this work.[35] Churchill's patronage circumvented the usual bureaucracy: de Grey reminded Angwin that invoking the support of the Chiefs of Staff would see "the necessary instructions to release the components will be issued forthwith."[36] De Grey also wrote to remind Angwin's superior, director of Telecommunications C.A. Taylor, that "the Prime Minister had instructed [General Ismay] to watch these matters on his behalf and to ask Departments for the necessary priorities."[37] Taylor replied that he was "arranging for the necessary authority to be issued at once."[38] This blank cheque from Churchill for Dollis Hill's work on Tunny is quite a contrast with the popular narrative that Flowers paid for much of Colossus from his own pocket.

The first prototype machine was dubbed Heath Robinson because of its ramshackle complexity.[39] Subsequent improved versions were also known as Robinsons. A month before Heath Robinson was assembled for the first time, Bletchley Park had already ordered "24 equipments similar to" the "experimental prototype constructed at Dollis Hill." They were "required for operational work at the earliest possible date" and so would be produced at in bulk at one of the Post Office's factories.[40]

Developing Heath Robinson as an assemblage of separately produced units created its own challenges. Tests at Dollis Hill on Heath Robinson's tape unit revealed problems with synchronization of its two tapes. In early June, de Grey complained to Radley that "the mechanical part of the machine which you are constructing has not in fact worked satisfactorily," making it unclear that it would ever work at the required speeds. Because "your part of the machine has not yet been attached to Wynn Williams' part" they could "not know that the

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[33] Ismay to Angwin, 20 February 1943, HW 62/5, TNA.

[34] The Postal Museum, POST 56/28, "The Maintenance of Post Office Services in War" (undated). Thanks to Mark J. Crowley for drawing this source to our attention.

[35] Radley to De Grey, 14 May 1943, HW 62/5, TNA.

[36] De Grey to Angwin, 16 May 1943, HW 62/5, TNA.

[37] De Grey to Taylor, 16 May 1943, HW 62/5, TNA.

[38] Taylor to De Grey, 21 May 1943, HW 62/5, TNA.

[39] Heath Robinson was a British cartoonist known for his depictions of implausibly baroque machinery, akin to the American Rube Goldberg.

[40] de Gray to Taylor, 16 May 1943, HW 62/5, TNA.

combination will work." He suggested a short delay in "embarking on production" of more Robinson machines.[41]

When the logic unit and paper tape assembly arrived at Bletchley Park on June 14, Wynn-Williams' counting modules were there, ready for integration.[42] Within two days Heath Robinson had successfully tackled a test message. Newman was cautiously optimistic, despite teething problems: "It is already clear that the general arrangements of both the punching and the scanning assemblies have been well thought out, and the use of the TRE counter is easily taught."[43] Newman noted that the mechanical approach required that scanning and counting processes were "absolutely reliable". This was not just a question of machine reliability: the wireless operators intercepting the messages had to work to new levels of accuracy, as did Heath Robinson's women operators. Much of this experience was directly applicable to Colossus, including the development of statistical techniques and tables needed to interpret the clues given by the counts the machines generated. [44] With Heath Robinson, Newman was prototyping not just a machine, but a complete socio-technical cryptanalytical system into which the Colossus machines would fit smoothly when they were delivered in the following months.

Colossus Was Authorized and Expected by Bletchley Park

Most prior accounts have suggested that Colossus was designed and built by Flowers and his team without the support or knowledge of Bletchley Park management. According to Randell, after "failing to get official support from Bletchley Park" for its development, "Flowers instead got the project authorized by Radley."[45] Copeland likewise suggested that Colossus was built without the support of the incredulous codebreakers.[46] Even Gannon, in the most archivally grounded overview of Colossus has stated: "Newman was supportive of Flowers and his design, but he was overruled as resources were scarce and senior figures were not convinced that electronics devices were reliable."[47] This evokes a classic popular narrative of innovation: a stubborn inventor defies orders to produce a machine that complacent men of power deem impossible.

Flowers' own memoir showed more nuance: because of worries about the reliability and speed of constructing an all-electronic machine, "it was decreed that work on the two-tape machine [Heath Robinson] should continue and have first priority…."[48] Flowers' suggestion that

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[41] De Grey to Radley, 8 June 1943, HW 62/5, TNA.

[42] Randell, "The Colossus," 63.

[43] Newman to Travis, Report on Progress, August 19 1943, HW 14/85, TNA.

[44] Donald Michie, "Colossus and the Breaking of the Wartime 'Fish' Codes."

[45] Randell, "The Colossus."

[46] Copeland, *Turing*, 103.

[47] Gannon, *Colossus*, 256.

[48] Flowers, "The Design of Colossus," 244.

Bletchley Park prioritized Heath Robinson, rather than rejecting Colossus, fits well with our archival evidence. The earliest discussion we found of what became Colossus is a March 1, 1943 note that Flowers had suggested "an entirely different machine, in which the message, and the wheels to be compared with it, would be set up on valves," rather than read from looped tape. Newman believed that this was "basically the right sort of approach" and that it would be "very much to our advantage to try out these techniques." He was pleased that Dollis Hill was "quite willing to follow up both lines at once" because the simpler, more adaptable tape machine would insure against the "risk of hold-ups along these new paths." [49]

Heath Robinson was then, almost from the beginning, the first phase in a larger development program including an ambitious electronic machine. After Flowers and Morell visited him on March 12, Newman noted they were "putting the simple machine with tapes first, as we want."[50] Gannon cited this letter as evidence that the proposed electronic machine was "turned down," but we are convinced that Newman still expected both machines to progress. [51] He told Travis that for "the more ambitious machine," the engineers "now propose to use tapes for the message and valves only for the fixed wheels. This does away with the main objection to their first scheme (lack of flexibility in use)." That set the basic parameters for Colossus: a single tape for the message coupled with electronics to simulate the Lorenz cipher wheels. Newman reported that "no date was given" for completion of the electronic machine, which he expected to process fifty messages a day, versus six to eight for the simpler one.[52]

Previous accounts suggest that Bletchley Park's leaders, having refused to support Colossus in early 1943, were astonished eleven months later when Flowers unexpectedly delivered a spectacularly effective machine. As Copeland put it: "In January 1944 Flowers' lads took Colossus—the world's first large scale electronic digital computer—to Bletchley Park on the back of a lorry. It caused quite a stir . . . . The codebreakers were astonished by the speed of Colossus."[53] In an early oral history, Flowers himself said "when the first machine was constructed and working, they obviously were taken aback. They just couldn't believe it! . . . . I don't think they understood very clearly what I was proposing until they actually had the machine."[54]

In reality, neither the capabilities of Colossus nor its delivery were unexpected. Newman's March 1943 discussion on the proposed machine's strengths and weaknesses, like his estimate that Colossus could tackle eight times more messages than Robinson, confirms he understood its potential immediately. The earliest archival use we have located for the name "Colossus" is 28 November 1944, when Newman told Travis that "pending the arrival of 'Colossus'" the Testery should handle "de-chied messages". By then Newman had a plan to "use

[49] Newman to Travis, "Report on Progress," 1 March 1943, HW 78/2, TNA.

[50] Newman to Travis, 12 March 1943, HW 14/70, TNA.

[51] Gannon, *Colossus*, 233.

[52] Newman to Travis, 12 March 1943, HW 14/70, TNA.

[53] Copeland, *Turing*, 104.

[54] Flowers, *Oral History Interview with Christopher Evans*.

Colossus in the first place mainly on difficult traffic, for runs too long to be done on the Robinsons."[55]

Why then the prevalent myth that Bletchley Park opposed Colossus? We believe it reflects a blurring of memory, misattributing the real hostility that Flowers' push for electronics provoked on the Enigma side of Bletchley Park to the unrelated work on Tunny that gave rise to Colossus.

Flowers always wanted to use more electronics, and always wanted to transfer work from other Bletchley Park partners to the Post Office. Letting him do things his way was not always the right call. In May 1943, amid his feud with Wynn-Williams over electronic sensing units for the Cobra bombe upgrades, Flowers had started a new battle. Keen at BTM had devised an all-new four-wheel bombe, dubbed "Mammoth," as an alternative to Cobra. He stuck with his firm's relay sensing technology, a challenge to Flowers and Wynn-Williams who were both convinced that electronic sensing was essential to any high-speed bombe even as they disagreed on how to implement it.

According to Gordon Welchman, who was overseeing the bombe upgrades, Flowers "made a violent attack on Keen." Radley had persuaded Edward Travis, operational head of Bletchley Park, to set aside Keen's Mammoth prototypes for a month as a testbed for electronic sensing. Flowers claimed to have discovered that Mammoth "was hopeless and the timing all wrong." Backing up his subordinate, Radley insisted that because Mammoth "would never work with relay sensing," Bletchley Park's "only hope was to let Flowers take the machine over and make it work." Radley allegedly threatened to "go to higher authorities" if Flowers did not get his way. Welchman also relayed a gripe from Wynn-Williams, that "Flowers' idea of co-operation is to run things himself." Welchman bemoaned Travis' "insistence on keeping Dollis Hill happy." He decided that for electronics "Wynn-Williams is the better man and I am now sorry we have not given him more support. He has been proved right and Flowers wrong…"[56] Flowers had by this point alienated everyone involved with the bombes. Welchman was perhaps worried that this threatened BTM's vital role as Bletchley Park's primary partner in the bombe program.

Flowers continued to seek evidence that relays would fail under heavy use at the speeds needed for Mammoth, but on August 9, Welchman concluded that "the arguments in favor of valves turned out to be very weak indeed."[57] He warned de Grey that "the reckless use of valves by Mr. Flowers" threatened to deplete precious supplies, and the "influence of Dr. Radley and Mr. Flowers must be completely removed."[58] Concerning work on Enigma, that is more or less what happened. The original plan was to build 34 Cobras and only six of BTM's Mammoths. On August 13, Welchman recommended capping Cobra production at twelve–none with Flowers'

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[55] Newman to Travis, 28 November 1943, HW 14/92, TNA.

[56] Welchman to A.D.(S) (de Grey), 4 June 1943, HW 62/5, TNA.

[57] Welchman memo, 9 August 1943, HW 62/5, TNA.

[58] Welchman to A.D.(S) (de Grey), 4 June 1943, HW 62/5, TNA.

electronic sensing unit.[59] Mammoths ultimately made up the bulk of the British high speed bombes.[60] The stubbornness of Flowers and Radley in promoting electronic sensing for the bombes does not fit well with the conventional story that, during the same mid-1943 time period, they chose to build Colossus in secret rather than openly challenge Bletchley Park's aversion to electronics.

Yet in November, just a few months after railing against Flowers' profligate use of electronics, Welchman was looking forward to the arrival of Colossus. Noting that "Flowers' valve engine, known as Colossus, is also nearing completion" he appealed to his contacts to procure the components needed to finish it.[61] Why did Welchman suddenly reevaluate Flowers? In October he had transitioned from running Hut 6, which only tackled Enigma, to head of a new "Machine Co-ordination and Development Section." The new job required Welchman to "take over all questions regarding the supply etc. of cyphering and deciphering machines" and chair a committee that included Turing, Wynn-Williams, and Newman.[62] According to his memoir, he "made contact with the very competent people who were handling" Tunny, but was "concerned primarily with what, if anything, they needed."[63] Given the well documented compartmentalization of work at Bletchley Park, Welchman may not have previously known that Flowers and Radley were doing vital work for Newman as well as tormenting Keen and Wynn-Williams.

Building Colossus

Previous accounts have been unable to accurately answer an apparently simple question: when did the construction of Colossus begin? This confusion reflects a more fundamental misreading of the relationship of the first Colossus to the Robinson program.

Copeland, for example, suggested that Flowers "worked day and night for ten months to build Colossus."[64] This picture of Flowers cloistered at Dollis Hill to work continuously on Colossus from March 1943 is hard to square with the evidence presented above that Flowers spent much of this period on other projects. In May, for example, he was often at Bletchley Park to supervise testing of the electronic sensing unit.

More importantly, several teams at Dollis Hill worked intensively on Heath Robinson from March to early-June 1943. Morell's team had the engineering expertise to drive paper tape at high speed, and Newman reported to Travis in March that the it had already cycled a tape loop

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[59] Welchman to D.D.(S), 13 August 1943, TNA HW 14/85, TNA.

[60] Radley to Travis, 20 November 1943, HW 62/5, TNA.

[61] Welchman to (Benjamin De Forest) Bayly, 26 November 1943, HW 62/5, TNA.

[62] Travis, "D.D.(S) Serial Order No. 117: Machine Co-ordination and Development Section," 10 September 1943, HW 14/87, TNA. His title was upgraded to "Assistant Director of Mechanization" in March 1944.

[63] Welchman, *The Hut Six Story*, 177.

[64] Copeland, *Turing*, 103.

at 2,000 characters per second.[65] Reading and processing signals from tape at such high speed was an obvious job for Flowers, given his passionate advocacy for adding electronic sensing to the new bombes. Flowers was working closely with Morell by March 1, 1943 and became a primary point of contact between Bletchley Park and the entire Post Office engineering operation.

It is clear, then, that the timespan during which Flowers is said to have built Colossus includes almost all of Dollis Hill's work on the Robinsons. Yet Copeland suggested that Colossus was proposed only after "Flowers did a redesign" of Heath Robinson. This "got the logic unit working" but "how to build a better machine" was a "question for an engineer." Flowers "in a stroke of genius… solved all these problems." After "Bletchley Park declined to support" this brilliant solution, "Newman himself" finished Heath Robinson, which was "always breaking down."[66] A casual reader might easily conclude that Heath Robinson was built at Bletchley Park, mostly by Newman, and served primarily to inspire Flowers by being inadequate.

As with much else concerning Colossus, the dominant narrative is based on Randell's early history, written before archival sources were declassified. Randell had Morell working on Heath Robinson from the summer of 1942 and installing it around April 1943. Flowers then arrived "to redesign the electronic counter, which had proved to be unreliable." Work on Colossus took place "in the incredibly short space of 11 months," from January 1943.[67] That sequence was internally coherent, but fell apart with subsequent evidence that, for example, planning for Heath Robinson did not start until 1943. Authors such as Copeland continue to assert two things that cannot both be true: Colossus took ten or eleven months to build and was only conceived after only after parts of Heath Robinson were tested and found wanting.

We suspect that Colossus moved to the foreground at Dollis Hill only around September of 1943, rather than February as the conventional narrative suggests.[68] There is a sense in which Flowers and his colleagues were indeed building Colossus from March 1943, but only because Robinson and Colossus were two parts of a single development program. Both machines processed bits selected from ten input channels (representing two bitstreams with five channels each). They combined these bits according to a logical expression set up on their controls, to tally how many times the expression was true during a full revolution of the tape holding the first sequence. As Newman's reference to using "valves… for the fixed wheels" makes clear, the fundamental difference was the source of the second bitstream. The Robinsons read from two looped paper tapes. Colossus generated one bitstream electronically, using circuits to simulate the Lorenz machine's code wheels. So, in principle, Colossus could be built by swapping out one of Robinson's tape readers for a few racks of electronics.

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[65] Newman to Travis, "Report on Progress," 1 March 1943, HW 78/2, TNA.

[66] Copeland, *Turing: Pioneer of the Information Age*, 72, 102-103.

[67] Randell, "The Colossus."

[68] Archival evidence is frustratingly sparse on this point. We found nothing in the Post Office archive, and no mention of what became Colossus in the Bletchley Park records from April to October of 1943.

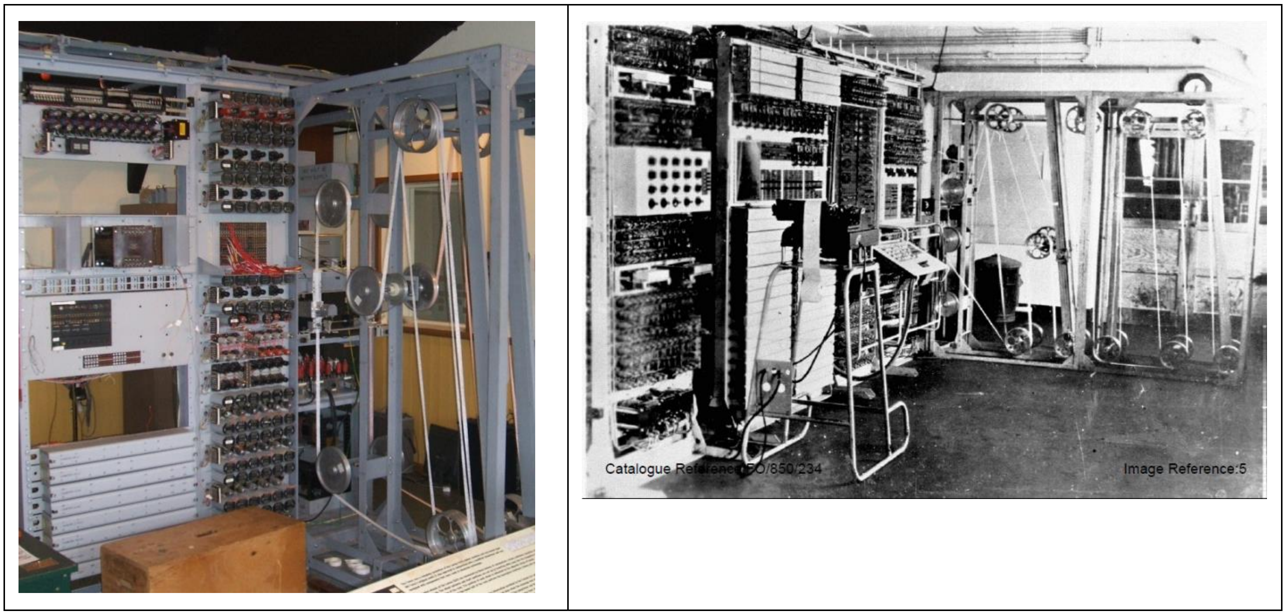

Figure 2: Heath Robinson, (L) as replicated in the U.K.'s National Museum of Computing at Bletchley Park, and an original Colossus machine (R). Both machines targeted the "Tunny" cipher. While Colossus was more efficient, substituting racks of complex electronics for the second tape reader used in Robinson machines, their structural similarities are readily apparent. (Source: Robinson photography by author. Colossus photograph National Archives (FO/850/234) used under the Open Government License v3.0.)

In practice Flowers made deeper changes, many when redesigning the Heath Robinson prototype as the basis for a large batch of Robinsons to be built by the Post Office factories. This gave Flowers an opportunity to prototype substantial portions of Colossus. By the summer of 1943 one of the four main Colossus subsystems had already been proven: the Heath Robinson tape reader. Work on electronic sensing for the bombes also offered another testbed for this technology. Two more Colossus subsystems, the improved logical combination and counting units, were designed and prototyped over the next few months for the production Robinsons.

Work on these units triggered yet another conflict with Wynn-Williams of TRE. Just as with the electronic sensing unit for Cobra, the Dollis Hill team wanted to redesign the Wynn-Williams designs. Allen Coombs began working on the Robinson logic unit around September 1943. He recalled that Wynn-Williams used tubes for amplification, rather than for switching logic. "In theory," he wrote, "the circuit was very ingenious; in practice it was a nightmare" getting the different stages, representing the logical addition of successive inputs, to work together.[69] Decades later Harry Fensom, a core member of Flowers' team, recalled "making enhancements to the Robinson, using Colossus-type circuits" to "replace the thyraton counters and XOR circuits" designed by Wynn-Williams. They were thus "able to prove some of the circuits and principles" needed for Colossus.[70]

[69] Coombs, "The Making of Colossus."

[70] Copeland, "Dollis Hill At War."

The prospect of endless tinkering worried de Grey, who had made Radley promise that "the design of Wynn-Williams' part of the machine should not be altered if it was established when the Post Office part of the machine was in operation that the combined effort did in fact deliver the goods." They "agreed that the temptation to alter designs in order to make minor improvements would be fatal to the output which was necessary if we were to get the first six machines within twelve weeks."[71] That late-August target was badly missed. In mid-September, Newman informed Travis that the initial batch would be at least a month late.[72] In fact the first delivery to Bletchley Park, in November, consisted of just two machines.[73] Perhaps Flowers and Radley slowed work down by prioritizing improvements needed for Colossus, though Post Office did not disregard de Grey's desire to replicate the prototype counters and the improved counters would benefit Robinson as well as Colossus.[74] More Robinsons, in several improved variants, eventually arrived, but because of the delays most of the work that Robinsons were originally expected to perform fell to Colossus machines.

Newman's attention had returned to Colossus that autumn, having gained a better idea of Heath Robinson's capabilities. In fragmentary notes made near the end of his life, Newman recalled being intimately involved in shaping the new machine: "Sept. 1943 the need for a much faster machine became clear & the facilities to be asked [sic] were intensively discussed with the math staff."[75] Another codebreaker, Jack Good, recalled that "the main specification" of Colossus was Newman's, and that "funds were made available" for it only after Health Robinson was successfully applied that summer.[76]

That leaves about four months for the detailed design and construction of the first Colossus, feasible only because much of the work had already been done for the Robinsons. Participants recalled manufacturing, fully assembling, and testing the first Colossus at Dollis Hill. Like ENIAC, it was designed exclusively by men but built in part by women: "the assembly and wiring were carried out by technical staff, including some of the wartime female assistants."[77]

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[71] A.D.(S) (de Grey), "Memorandum of Meeting with Dr. Radley – Fish and Counting Machines (Mr. Newman)," 29 May 1943 HW 62/5 HW, TNA.

[72] Newman to Travis, 14 Sept 1943, HW 62/5, TNA.

[73] Newman to D.D.I., 12 March 1944, HW 14/99, TNA.

[74] A year later, Newman wrote that Wynn-Williams could have six of his "valve and relay" counters stockpiled at Dollis Hill. "It is unlikely that anyone else will want them" noted Newman. We presume these were for the anticipated large batch of Robinson machines, but became obsolete with the shift to what Newman called the more "satisfactory Flowers all-valve counters." Newman, 3 June 1944, HW 62/6, TNA.

[75] Newman, untitled handwritten notes in response to Randell, Max Newman Papers (St. John's College Library, Cambridge, UK) box 3, folder 3.

[76] I. Jack Good, "Pioneering Work on Computers at Bletchley."

[77] Coombs, "The Making of Colossus"; Haigh, et al., *ENIAC in Action*, 61-62, 298.

That work must have focused on the fourth major Colossus subsystem, the only one not needed for an improved Robinson: the electronic assembly used to simulate the Lorenz cipher wheels. It accounted for most of the approximately 1,600 vacuum tubes in the first Colossus. Gil Hayward and others in Flowers' team had already used slower electro-mechanical technologies to simulate the code wheels in a machine that punched cipher wheel sequences onto paper tape. These tapes were an essential part of codebreaking practice using the Robinsons. Colossus integrated the capability using electronic ring circuits. Their output was fed directly into the logical combination unit.[78]

Colossus in Practice

On January 2, Newman informed Travis that "Colossus will (optimistically) arrive in 10 days." He viewed mid-February as "a reasonably hopeful date for starting serious production."[79] According to Flowers' diary, Colossus arrived at Bletchley Park on 18 January 1944 and completed its first job on 5 February.[80] Heroic accounts of technological innovation tend to stop with the first operation of a machine. They assume that it was reliable, immediately displaced inferior technologies, and required little human labor to function. None of those things were true of Colossus.

Maintenance and innovation were inseparable. Rather than working flawlessly from the moment it was delivered, as most accounts suggest, Colossus required months of adjustment. According to Chandler, the existing cabling did not fit with the new layout so "totally new cabling and cable supports had to be made to complete the assembly."[81] Once cables were fitted, "during the initial operation period, many of the valves failed—usually catastrophically . . . . ."[82] A February 23 report noted that Colossus was "in continual repair."[83] On March 12, Newman still listed "Colossus 1 completed (20th March)" as a future event. It was already tackling around 15 messages a day, versus one for each operational Robinson, and Newman expected that to rise

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[78] To learn more about its capabilities, see Priestley and Haigh, "Colossus: The Missing Manual."

[79] Newman to Travis, 2 January 1944, HW 62/6, TNA.

[80] Flowers' family granted us access to his diary for 1944, scanned by the National Museum of Computing at Bletchley Park.

[81] Chandler, "The Installation and Maintenance of Colossus."

[82] Chandler, "The Installation and Maintenance of Colossus."

[83] John H. Seaman, "Fish Material," 23 February 1944, in National Archives and Records Administration, College Park, MD (hereafter NARA) RG 0457, container 1009, Folder "Fish Notes."

to 20.[84] On March 29, de Grey informed Radley that the first Colossus was “now shortly coming into full operation.”[85]

Neither class of machine achieved the throughput Newman had anticipated a year earlier.[86] However, the observed 15:1 advantage of Colossus over Robinson was even greater than the 8:1 advantage Newman had predicted. Colossus allowed more efficient routines for “wheel setting:” the pin configuration of the encryption wheels was known but not the start position of each wheel. Because it generated the encryption wheel bitstreams electronically, there was no need for operators to prepare tapes for every new wheel configuration. These were changed by setting pins on its control panel. Reading only one tape eliminated the need for mechanical synchronization, allowing the Colossi to spin their tapes at five thousand characters per second.

This article cannot fully describe codebreaking practice around Colossus, a topic so far considered primarily from the viewpoint of gendered labor.[87] Although Colossus is often said to have “decrypted” Tunny messages, decryption was actually carried out using separate machines, once the wheel settings had been figured out. By the end of the war, codebreakers had devised ways to use Colossus to set and break all twelve of the code wheels. In practice, the Colossus machines were usually reserved for the tasks hardest for unaided humans. The diagram in figure 3 gives a sense of how Colossus was typically deployed. Once the Newmanry had determined settings for the five Chi wheels with the aid of Colossus, it passed the message to the Testery, where a different team manually figured out the start positions of the other wheels and decrypted it.

[84] Newman to D.D.I (de Grey), 12 March 1933, HW 14/99, TNA.

[85] de Grey to Radley, 29 March 1944, HW 62/6, TNA.

[86] Perhaps because in December 1943 the Germans had implemented an additional encryption process dubbed “autoclave.” Reeds, et al., *Breaking Teleprinter Ciphers*, 308, Sect. 344C.

[87] Abbate, *Recoding Gender*; Hicks, *Programmed Inequality*.

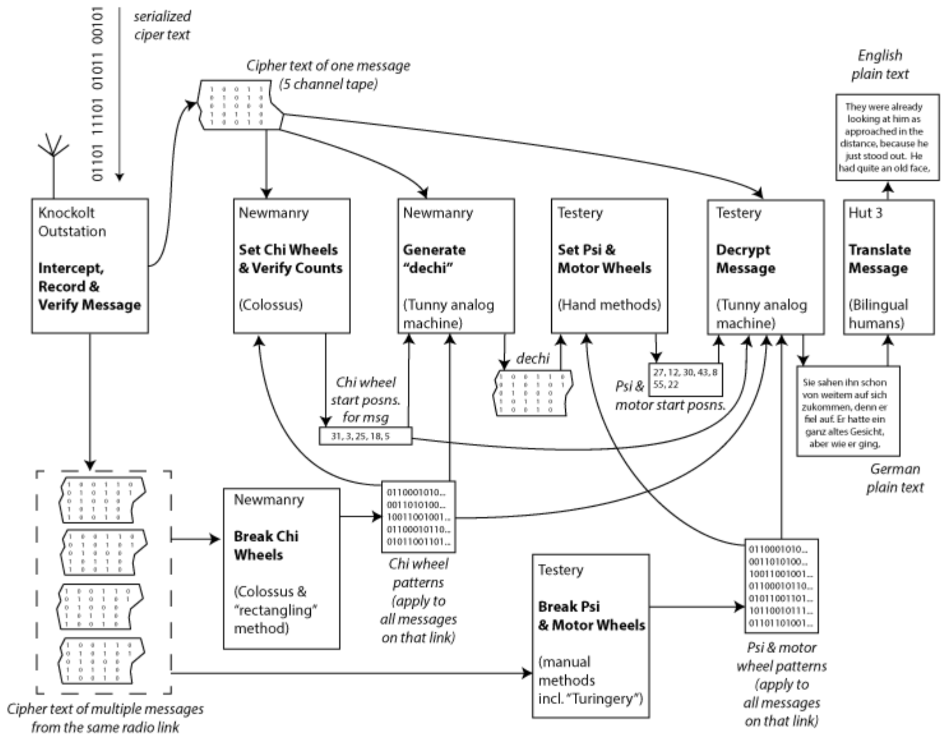

Figure 3: Rather than automating the decryption of intercepted German "Tunny" messages, Colossus was typically applied to speed up the most labor-intensive tasks in what remained a complex and highly skilled collaborative process carried out by several groups within the Bletchley Park codebreaking complex.

Even tasks carried out with Colossus involved much more than loading the tape and pushing a button. Finding settings for one message often required many runs through the machine. The usual partnership was between a female Colossus operator, working hands on with the machine, and a male cryptographer who interpreted the results and decided what to try next. As both built up experience, the effectiveness of the Colossus machines increased substantially. Operators got better at jobs like mounting and unmounting paper tapes in the elaborate high-speed reading apparatus. They learned how to flip racks full of switches to run batches of short jobs, such as character counts to confirm wheel settings, in a few seconds each. Experienced cryptographers read clues in the output of one run to reveal the most effective follow-up. They captured this expertise in decision trees to guide less experienced colleagues.

Flowers told an interviewer, "Once the first Colossus was a big success, we expected Bletchley Park to ask us to make a lot more, but they didn't. We never heard from them."[88] He recalled being so confident that he nevertheless ordered the construction of more Colossus parts, stockpiled to meet the big order when it finally arrived with an impossibly tight deadline. This oft repeated claim is contradicted by evidence that Bletchley Park staff were anticipating further

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[88] Flowers, *Oral History Interview with Christopher Evans.*

machines even before the first was fully operational.[89] On February 7, 1944, Newman wrote, "The future is… brighter in that Flowers now promises a Colossus 2, which is far speedier than Colossus 1; and should therefore more than double the output; and that Colossus 3 is not quite so remote as it seemed."[90]

By February 23, an American embedded at Bletchley Park could already describe the key advantage of what he called the "super-colossus": evaluating not one but five different combinations of code wheel start positions during each loop of the message tape.[91] Later machines incorporated many tweaks to boost productivity–for example adding plug panels on the front so that operators did not need to constantly dive around the back when using it to determine wheel patterns ("wheel breaking"). Hardware and practice evolved together.

The success of the first Colossus shifted production demand from Robinsons to Colossi. Coombs recalled being reassigned from the Robinsons to head development of the second Colossus soon after "the very successful demonstration of the Mark I Colossus."[92] The manufacturing effort gobbled up more space at Dollis Hill. In 1977, in the first report on Colossus in the Post Office Electrical Engineer's Journal, Coombs hoped "erstwhile Dollis Hill group leaders… denuded of staff and laboratory space and squeezed out for workshops" might be consoled by learning why they had been displaced.[93]

Flowers tore his draft design for the improved machine into pieces and handed them to senior engineers to work up detailed treatments of different units. These treatments were "handed over to other engineers . . . to lay out the circuits for assembly on standardized plates." According to Coombs, "such was our confidence in the new techniques" that "we would specify forthwith the new circuits required in the sure and certain knowledge that they would work…. The habit of confidence was hard to break." The freedom to jump from idea to full-scale implementation could flourish within a bureaucratic organization like the Post Office only within this tight knit group and only during emergency conditions. After the war, Coombs "once blandly suggested that such and such would be the circuit I would use . . . they wouldn't want a mock-up or anything would they?" He "was quickly disabused. War is one thing; peace is another."[94]

Demand for Colossus meant that later machines were manufactured on an industrial basis in the Post Office factories, as had been the plan with Robinson. In late April, Flowers and Radley promised that the delayed Colossus 2, 3, and 4 would arrive in June, July, and August,

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[89] "Non Morse Transmissions," Lt. Col. Pritchard, 7 February 1944. HW 14/97, TNA.

[90] Newman, 7 February 1944, HW 16/97, TNA (Untitled note responding to Pritchard's report).

[91] John H. Seaman, "Fish Material," 23 February 1944, in NARA RG 0457, Container 1009, Folder "Fish Notes."

[92] Coombs, "The Making of Colossus."

[93] Coombs, "Colossus and the History of Computing."

[94] Coombs, "The Making of Colossus."

followed by the "factory-made Colossi" in October.[95] Travis officially ordered eight more on May 1, telling Radley "your first Colossus is doing great work and . . . its design and construction seem to me to have been a magnificent job."[96] A few days later the second Colossus arrived at Bletchley Park, and within a month it was in operation.[97]

The speedy design and production of the improved machines relied on the Post Office's well-established systems of engineering and production, with their clear hierarchies of skill, labor, and gender. Assembly and wiring "first at Dollis Hill and later also at the Birmingham factory" were done by "small squads, under more experienced skilled workmen." [98] As before, many of the "wiremen" building subassemblies were women. The different panels were only mounted on racks and integrated into working machines on-site at Bletchley Park, by around fifteen "very bright" Post Office technicians, who also maintained the completed machines.[99]

By July 1944, Welchman was hoping to extend the institutional partnership with Dollis Hill into peace time. He told Travis that "Flower's [sic] development of thermionic apparatus has been behind the success with Fish … I hope that we shall be able to keep in touch with Keen and Flowers after the war, and that we shall also be able to make use of the manufacturing facilities at Letchworth and Dollis Hill."[100]

Colossus as a Special Purpose Machine

Work decoding old Tunny messages continued after the German surrender, finishing on 8 July 1945.[101] The subsequent decommissioning of most Colossus machines is sometimes presented as an act of wanton barbarism. According to Copeland, for example, "Bletchley's electronic computers, the most sophisticated machines in Europe, were smashed to pieces." "Turing, Newman and Flowers" would otherwise "quickly have adapted" them for scientific applications. "With eight massive electronic computers in the public arena from mid-1945," mused Copeland, "the Internet—and even the personal computer—might have been developed a decade or more earlier.[102] In fact, Newman himself recognized that Colossus was too tightly coupled to the specifics of Tunny to be useful for other purposes. Rather than smash the machines, he devised a careful plan to recycle their components.

Brainpower and engineering expertise were relatively plentiful in Britain during the war, while materials and manufacturing resources were scarce. Contemporary observers saw reliance on high performance, special purpose machinery epitomized by Colossus as a hallmark of the

[95] Welchman to Travis, 1 May 1944, HW 62/6, TNA.

[96] Travis to Radley, 1 May 1944, HW 62/6, TNA.

[97] Dates taken from Flowers' diary.

[98] Coombs, "The Making of Colossus."

[99] Chandler, "The Installation and Maintenance of Colossus."

[100] Welchman to Travis, 10 July 1944, HW 62/6, TNA.

[101] D.D. (1) (de Grey), "FISH," 9 July 1945, HW 62/6, TNA.

[102] Copeland, *Turing: Pioneer of the Information Age*, 118.

British approach to codebreaking. Alongside Britons' general enthusiasm for specialized technological gadgets that David Edgerton persuasively attributed to Churchill, this reflects a unique alignment between the cultures and institutional capabilities of Dollis Hill and Bletchley Park.[103] Walter Jacobs, an American mathematician and codebreaker posted to Bletchley Park, reported to his superiors that "their readiness to design elaborate and expensive equipment for problems of sufficient importance" yielded equipment that "answers fully the specific needs of the particular problem and will frequently be of far greater value than any general equipment."[104] A British visitor to the U.S., in contrast, marveled at "the apparent prodigality in the use of man and machine power . . . the seemingly inexhaustible supplies of every kind of stationery and gadgetry." Instead of asking "could this be done by machine," Americans asked "how can this be done by machines," leading to "a determination to make use of IBM [tabulating machines] at every stage in the cryptographic process."[105] According to historian Colin Burke, the American army's Signal Intelligence Service (SIS) alone enlisted "close to 400 IBM machines using a million IBM cards a day." By the end of the war there were 1,200 workers in its tabulating rooms.[106] Bletchley Park's relatively small tabulating machine operation primarily indexed decrypted intelligence rather than assisting decryption.[107]

Yet, as James A. Reeds, Whitfield Diffie, and J.V. Field noted in a recent examination of work to break Tunny, the speed of Colossus came at a cost.[108] The conventional story is that fast, reliable, and flexible Colossus displaced slow, unreliable, and inflexible Robinson. That narrative is bound up with a teleological sense of historical movement towards electronics, captured in Wikipedia's explanation that Heath Robinson "was mainly an electro-mechanical machine, containing no more than a couple of dozen valves (vacuum tubes), and was the predecessor to the electronic Colossus computer."[109]

Colossus was indeed faster to configure than a Robinson, but that advantage is more properly termed convenience or efficiency rather than flexibility. The Robinsons could compare any two bitstreams punched onto tape, making them truly flexible, whereas the second bitstream processed by Colossus was hardwired to the geometry of the Lorenz machine wheels.

Colossus was thus obsolete the moment the Germans surrendered. Newman told Travis that after "work on Fish comes to an end…. there will be no further use for Colossi, but some specimens will be wanted for further investigations." He proposed keeping two entire Colossus

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[103] Edgerton, *Britain's War Machine*.

[104] Walter Jacobs, "Temporary Duty with the 6813th Sig. Sec. Det," 14 April 1945, NARA RG 0457, Container 943, folder "Cryptanalysis of the Tunny Cipher Device."

[105] A. Mitchell, "Personal Report No. 6"12 August 1945, in NARA RG 0457, Container 1328, "Personal Reports from Captain Mitchell" folder.

[106] Burke, *It Wasn't All Magic*, 431.

[107] Brunt, "Indexes at the Government Code and Cypher School, Bletchley Park, 1940-1945."

[108] Reeds, Diffie, and Field, *Breaking Teleprinter Ciphers*, 538-539.

[109] Wikipedia, "Heath Robinson (codebreaking machine)."

machines, setting aside the tape readers and counters from the others for possible use on "the computing-machine research units which are being projected at the NPL and elsewhere." Contrary to Copeland's fanciful suggestions, Newman well understood that Colossus was most useful to computing groups, such as the one he was soon to lead at Manchester University, as a source of parts. "The counters in particular," he wrote, "have little value as scrap but are of great value as they stand." The "other racks," including the cipher wheel simulators, "cannot be reused and should be returned to Dollis Hill for breaking down."[110]

Newman anticipated that the Robinsons, in contrast, would remain useful "not only for research work on new problems, but perhaps also for doing low grade work." Travis ordered the "Robinson research group" kept intact, along with the four newest Robinsons and associated tape preparation machinery. Robinson development outlasted Colossus production. The United States turned down the offer of a Colossus at the end of the war, but was keen to acquire a Robinson. This prompted the observation that the "versatility of ROBINSON [is] becoming constantly apparent."[111] British intelligence recruited staff from the Post Office and the British Tabulating Machine Company to bring engineering capabilities in-house, creating four new Robinsons with "Colossus type circuits, tape readers, and output printers."[112]

Travis followed Newman's recommendations by preserving two of the ten Colossus machines, retaining only counters and tape equipment from the others.[113] Government Communications Headquarters, the successor to Bletchley Park, confirmed the retention of two machines in its classified history of Colossus: "the nature and reliability of the machines was such that a number of attempts, some more successful than others, were made over the years to adapt them to more general tasks."[114]

Uniquely Successful, Not Uniquely Ambitious

Colossus is often singled out as unique in its large-scale application of digital electronics, and therefore the most significant waystation on the path to the modern computer (or even as itself the first computer). When first publicizing the machine, Randell asserted "there were no earlier or contemporary electronic machines in the American communication operations that matched the size or complexity of Colossus."[115] Subsequently declassified records reveal this to

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[110] Newman to Director (Travis), "Disposal of Machinery," 3 June 1945, HW 62/6, TNA.

[111] G.C. & C.S. (i.e. Bletchley Park) to S.S.A. Washington, 26 August 1945, HW 57/1, TNA.

[112] Lavington, "In the Footsteps of Colossus: A Description of Oedipus."

[113] J.W.J. Herivel to Travis, "Disposal of Fish Machinery," 9 July 1945, HW 62/6, TNA. The retention of four Robinsons and two Colossi is noted in Herivel to "Director" (Travis), 31 July 1944, HW 57/1, TNA.

[114] D.C. Horwood, "A Technical Description of Colossus 1," August 1973, HW 25/4, TNA. Quote on page 1. We suspect that their special-purpose cipher wheel simulators were replaced by more flexible magnetic drum memories. Research by Simon Lavington suggested that the last adapted Colossus was in use until about 1961. Lavington, "In the Footsteps of Colossus."

[115] Randell, "The Colossus."

be false: several other wartime codebreaking projects combined high speed electronic processing with the rapid reading of stored messages. Colossus was not even the most technologically ambitious. It was, however, by far the most useful. Briefly comparing Colossus to those other projects helps us understand just how contingent its success was on the strength of the partnership between Dollis Hill and Bletchley Park.

Jacobs, the American observer, had cautioned that building special purpose machines, of the kind favored by Bletchley Park, was a gamble. Building one offered huge potential speed-ups but was a longer, risker process than using proven technology. Such machines "take many months to design and build and are subject to constant modification as their 'inadequacies' become apparent. During the waiting period for the machines, there are no devices available to work as stopgaps."[116] Projects based, as Colossus was, on unproven or emerging technologies were particularly prone to failure.

The most obvious difference between Colossus and most of the ambitious American codebreaking machines is that it worked properly. Several unsuccessful projects chose microfilm for storage, which promised an increase in capacity comparable to the processing speed increase offered by electronics. MIT professor Vannevar Bush was already a celebrated expert on machine computation during his attempts in the late-1930s and early 1940s to build hybrid electronic-microfilm cryptanalytic machines. As chronicled by Burke's *It Wasn't All Magic*, they was a painful series of fiascos. Bush tried to run a serious engineering project with graduate student labor, a contrast with the industrial professionalism of Dollis Hill.[117]

Some machines were finished but entirely failed to match their original design goals. The U.S. Navy commissioned Amber, a Colossus-like electronic machine that used microfilm for storage. It tested only 800 characters a second, versus the 335,000 initially targeted, and "took over 800 hours of tabulator and IBM electro-mechanical multiplier time" to prepare each microfilm input deck.[118]

Were Flowers and his colleagues lucky that their telecommunications experience led them to couple electronic processing with paper tape rather than film storage? Perhaps, but the same combination defeated other groups. In mid-1942, well before Colossus was conceived, an MIT-trained engineer began to develop the "Freak" for the American Signals Intelligence Service. Like Colossus, it used high speed electronic counting circuits to process data read from paper tape readers. Two years later the Freak was abandoned. Neither its counters nor its electronic memory, built from seven thousand condensers, ever worked reliably.[119]

The difference in reliability between machines produced by Post Office engineers and by these less experienced groups is striking, and can be explained by its distinctive engineering culture. Everything the Post Office built had to be exceptionally reliable because its customers

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[116] Jacobs, "Temporary Duty."

[117] Burke, *It Wasn't All Magic*, chs 2-3.

[118] Burke, *It Wasn't All Magic*, 188-189.

[119] Burke, *It Wasn't All Magic*, 129-130.

relied on uninterrupted service. Telephones were not routinely serviced. Transmission equipment was spread out and telephone exchanges were situated close to customers, putting a premium on unattended operation round-the-clock. Engineers had often begun their careers maintaining this equipment.

Machines that worked only after the war had finished were little more useful than those that never worked. Ten entire Colossus machines were designed, built, and deployed while there was still Tunny traffic to decrypt. In contrast, the first of twenty planned Amber systems arrived after the Allied victory.[120] Still undergoing tests at Bletchley Park was another American machine, the 5202. It was similar to Colossus but used film instead of paper tape.[121] Elsewhere, a U.S. Army team built "Superscritcher" from more than 3,500 vacuum tubes, far more than Colossus. To crack Enigma, it simulated cipher rotors electronically, automatically stepping their positions and printing settings when a possible hit was detected. It too was built in vain.[122]

Even a well-engineered machine completed in good time was operationally worthless if specified without access to cryptographers who understood exactly how to attack the code in question. Bell Labs, the American equivalent to Dollis Hill, had the engineering and production capabilities to rapidly produce reliable machines. Its massive electromechanical bombe system, codenamed Madame X, cost a million dollars but accomplished little. During its design phase, the British refused to share techniques for Enigma work. Despite many efforts to develop methods suitable for the machine, the Signals Intelligence Service "had to admit defeat and had to yield to England's monopoly of methods and its control of intercepts."[123] In contrast, the Dollis Hill team worked very closely with Newman to deliver a machine that did exactly what was needed, and to tweak later Colossus models to support new cryptographic techniques.

After a deal to share Enigma secrets, the next American bombe project, by office products company NCR, was a success. The 121 so-called Dayton Bombes, delivered from mid-1943 onward, were the most complex mass-produced electronic devices of the war. Each used hundreds of tubes for comparisons, control circuits, and counting. [124] That NCR and Dollis Hill were each able to build a reliable machine out of unreliable vacuum tubes suggests that this was less of a technological rupture, as profiles of Colossus and early computing projects often suggest, and more a careful application of professional engineering practice.

Colossus in Social Context

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[120] Burke, *It Wasn't All Magic*, 186-189.

[121] Reeds, et al., *Breaking Teleprinter Ciphers*, 456-470, Sect. 491, Sect 530-534.

[122] Crawford and Fox, "The Autoscritcher and the Superscritcher."

[123] Burke, *It Wasn't All Magic*, 140. Early designs called for 1,500, but the final version consolidated four sets of electronic elements into each glass envelope, shrinking the count to less than 500. Jennifer Wilcox, of the National Cryptologic Museum, told us that with a "flashlight and a step ladder" she counted 294 externally visible tubes in the museum's example.

[124] DeBrosse and Burke, *The Secret in Building 26*.

Colossus is often presented as a story of idiosyncratic genius: a brilliant inventor and a handful of assistants developed a revolutionary new machine, persevering despite the active hostility of Bletchley Park's leaders to electronics. Throughout 1943, Travis, de Grey, and Welchman indeed favored proven technology; not only for the higher speed bombes, urgently needed to restart industrial-scale breaking of Enigma after the Germans tightened security, but also for the Robinson machines essential to routinely breaking Tunny. We found no evidence of hostility to the simultaneous development of Colossus, a higher performance, higher risk machine for which the extensive use of electronics was appropriate, indeed essential. When it came to electronics, Flowers was the proverbial man with a hammer, to whom everything looks like a nail. In his reminiscences long ago projects blurred together, giving the impression that the enemies who thwarted his plans for the bombes had also tried to block Colossus.

In contrast, archival records tell a story of productive collaboration between two quite different institutions. The popular story of Bletchley Park is one of brilliant improvisation by people like Turing, Tutte, and Newman whose pre-War scientific work was quite unrelated to their wartime duty. This fits the British love of gifted amateurs and distrust of professionalism and grinding preparation. Bletchley Park was, as social histories have shown, a much larger and more diverse place than this acknowledges, yet most of the figures named in our narrative, who held senior positions, were from middle- or upper-class backgrounds and had been recruited from academic or corporate positions. Even Tutte, the son of a gardener and a housekeeper, followed a narrow but proven path of social mobility with a series of scholarships that took him to Cambridge University.

The Dollis Hill side of the collaboration looks different. Flowers and his colleagues invariably stressed continuities between the engineering challenges they overcame during the war and those of telecommunications engineering. Unlike our Bletchley Park characters, of whom only de Grey, Travis, and Tiltman were career intelligence professionals, they worked within a stable institution. Methods used to specify, design, and produce the Colossus prototype, and manage the rapid completion of nine further machines, evolved from pre-war Post Office practice. The wartime availability of these institutional and technical capabilities was no lucky accident. It testifies to the British state's investment during the lean years of the 1930s, and to the openness of Dollis Hill to men from humble social backgrounds. Flowers came from a poor family and joined the Post Office as a "provisional inspector" after completing a vocationally oriented technical education. His skill with electronics drove a transfer to its Research Department and exceptionally rapid rise through its ranks. At the age of twenty-seven, he earned a first-class London University engineering degree after years of night school classes taken at various institutions founded explicitly to serve the working class. Broadhurst, another key member of the team, joined the Post Office as a laborer. His rise to a career in engineering research began with a promotion to maintain telephone exchange equipment. Bletchley Park's other crucial engineering collaborator, Harold Keen of BTM, had followed a similar path through the ranks after joining that company at eighteen.

These differences reflect broader tensions between the social worlds, and classes, of science and engineering. At a time of national emergency, the Colossus project brought them together, building collaborative personal relationships within a larger supportive matrix of institutional partnership. The difference between Colossus and the many failed projects was not just Flowers' exceptional skill as an engineer. Only as the lynchpin of an alliance between Dollis Hill and Bletchley Park could he mobilize the full range of technological expertise, tacit knowledge, and manufacturing capabilities to package several novel technologies into exactly the form needed for the attack on Tunny. Perhaps that was genius. It was not, and could never be, lone genius.

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