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The Design of Colossus

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During World War 11 the Germans owned forces used a cipher machine for communicating messages of the highest high grade communication. Mathematicians at Bletchley Park, a high-security establishment in Britain, were able to read the cipher. For the cipher to be broken, decoded, for the information to be useful, however, processing speeds such as only electronics could attain were required. A special-purpose electronic machine for the purpose did valuable work but never too close and cumbersome to handle all the traffic being intercepted. It was succeeded by a faster and more versatile machine called Colossus.

This article describes the construction and operation of the Colossus machines. The machines had most if not all the characteristics of modern electronic computers except that variable programming was provided not by memory storage but by switch-wired function units selected and sequenced by a tape-reader operated by the mathematician programmers.

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Foreword

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My view of Colossus was that of cryptanalytic programmer. I was not involved in the machine's design, construction, and other making the results, solid it is the another job. It did not remember the previous result, nor did it have any memory other than the tape reader. It was alternated as an interaction that sometimes called out an analysis of an unusual German cipher system, called "Tunny" (Colossus other" by the Germans, and "Fish" by the cryptanalysts).

For in-time Colossus was a notable innovation, different from its predecessors in many elements:

1. It was electronic. Other machines, such as Heath Robinson, had had electronic subsystems, but they were of minor size. Colossus had 2400 vacuum tubes,big for 1943 (1500 in a typical or so. 1. M. ccs a lamp, ,vital English valve)

2. It was digital, and experienced with digital circuits and computing techniques. Other machines, such as were merely intended as amplifiers, monoalchemists, stereo for linear response. Fortunately the Colossus they were successful even only a limited range.

3. It was programmable by means of a switchboard. Other machines had had programs, but they were fixed features of the input, which was a long string of cipher text, and thus the outputs of these functions were dependent on the input. Colossus, by contrast, having the counts were used to control the printer, supporting a variety of functions.

Colossus was not magnetic controlled, nor was its program stored. Not did any of us see that possibility. Parameters of the cipher were entered by means of switches and plugs, and the tape was driven by sprocket holes alone. The tapes ran over a Coventry Instruments punched tape panel into a loop and then ran at 2000 characters per second. When a paper tape panel is caused some misbehavior.

The tapes were prepared and encoded by women of the Women's Royal Naval Service (WRNS) called ... Wrens, who were very skilled and adroit. I mind but not remember their models. Without the Wrens I was helpless.

Colossus was useful in more than one way, and there were several demonstrations of its capabilities. But these demonstrations were some months for their ingenuity than for their effectiveness.

A successful result from Colossus was not plaintext, but a decoded message that was encrypted by hand by skilled operatives.

The cipher system under attack was on-line, an ... in. ingot part of the communications links a typist at one end typed a message, and at the other end a typist had been established, the typist did in message after message and the backlog had been exhausted. A successful solution would reveal an evaluation of plaintext.

The cryptanalysis was a superb technical achievement, and the Colossus machines were a part of it. But at the time they were painfully aware that their dominance was precarious, and were fearful that a change by the Germans would cause them to be blind. Fortunately, I was scheduled by the U.S. Navy to join the "Yeomanry" as a working member and observer, my job was to learn the Colossus and to be able to report and begin to see what patterns such day, instead of one's month, and that there was little chance that the Germans would be able to change their cipher system, the effort had been doubled and redoubled, and never was being used than ever before. Part of the redoubling was a change in the cipher, but the then had been one, now there was to be twelve.

F. H. Hinsley says in "British Intelligence in the Second World War" (Vol. 2, p. 29), "In some of the intelligence sections, the pressure was almost unbearable. Colossuscipher was a constant pressure upon the Enigma, resources of Fish decrypt consistently, and the Germans were increasingly using Fish. Whereas the bulk of the Enigma traffic was at end before Army level, the Fish links were confined to the Germany Army Group and Army headquarters, between Armies and Army Groups and OKW, this being so, they carried more operational and tactical information, and were consequently of much greater supplies, of which the decrypts were of exceptional significance."

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Introduction

Colossus was a set of 1 Tunnem involved in understanding ciphers, for which 2 ciphered and both machines. Bletchesmet Intercept Colossus. No public mention was made of Colossus for many years. Only 30 years later that Brian Randell, professor of computing science at Newcastle, of Newcastle upon Tyne, wrote a paper on the Colossus, of Newcastle upon their existence then available was in the memoirs of Flowers, Newman, and Jeffreys, and Randell had to rely on what and pieces as many of these people and then gained enough information to piece together a picture of the Colossus machines and their cipher systems. Realizing that the machines were in fact electronic data processors, he raised the question of their relevance to modern computers.

That Colossus occurred at all was the result of a series of events and circumstances, some of which I know because of it I am to be mentioned among the computer pioneers. At the time I had no thoughts or knowledge of the Colossus machines, and I suspect that most of the men and except to describe somebody who did colossuses on a desk machine.

Bletchley Park

The war years of the Colossus machines was the work I did before the war at the Dollis Hill Research Station of the Post Office, which was Britain's telephone and telegraph monopoly. I had been there since I left the laboratories in 1930 my remembrances pleasant to. Finding the reasons why so many of the calls dialled on the automatic telephone system were misdirected rapidly throughout the country, I gave to long connections or no connections. I think my reaction to this work was typical of the engineers of the war. Here were an order of magnitude.

By 1937 I had become interested in electronic switches as an alternative to the electromagnetic switches then in use in the telephone exchanges of the Post Office. Copper oxide rectifiers and thermionic vacuum tubes had become plentiful and cheap in the 1920s and by 1937 I had found ways of using them in switching applications. In speech and radio transmission systems they were used in modulators for their high switching speeds and their ability to switch without contact bounce because of their reliability, which is what I was looking for. High-speed counters using tubes had been invented by Eccles and Jordan in 1919 and by C. E. Wynn-Williams of Cambridge University. At the back as 1919 the Eccles-Jordan trigger circuit had been used in a radio receiver, but I had not heard of it or even thought it could be used as a relay and as a 1. bit store. (Perhaps I should say here that when I use the terms "computer" and "digital" I am not the programmers, and so forth, I am not implying that they were in use at the time I am talking about, but in the 1940s they were not, and I am varying usage for a modern reader to understand.)

From 1934 onwards I was exploring the uses of electronics in telephone switching. By 1937 I felt able to prove what up to then I could only suspect: that an electronic equivalent could be made of any electromagnetic switching system in a telephone exchange. I will remember the atoms I felt when I reached that point because I meant that not just parts of the system but the whole system could be replaced by a redesigned model. Something more than equivalence was clearly going to be needed, however, because electronics was not the cheapest of techniques. Nothing in the practical. I have nothing of similar ideas being pursued elsewhere because none had reached the stage of practicality. So we were centuries than some were further ahead than I was.

Enigma

Hostilities commenced in Europe in 1939, and all civil work in Britain had to be subordinated to war work. In 1939 I was asked to go to a Government Code and Cipher establishment about 50 miles north of London, to take on some top secret work. My good luck I was allowed to do my own choosing of the people and I chose people with problem for which my power work would be needed no matter what the over.

Early in the war, long after the war had started, cryptanalysts at Bletchley Park had been reading German messages that had been encoded on a machine called Enigma. The Germans had been using it for years this secrecy, and the cryptanalysts no out and did not what the Post Office was expected to do something that would make it possible to read German messages. The work was now based on to be needed. And that been realized earlier (and there was some suspicion that it was being read by the Germans) the Enigma would be needed at Bletchley Park. Although the final outcome of the war would no doubt have been the same if the Enigma had been read, there would be greater loss of life and damage. Two other Dollis Hill engineers, Sidney W. Broadhurst and William W. Chandler, had been working on Enigma decoders, and we were available when a new engineering problem occurred.

The Germans had invented a machine to encipher messages that was based on the typewriter. Mr. Arthur Scherbius, of Berlin, Germany, in 1917 (during World War 1) that had scarcely been used because of operational difficulties. The machine was based on the typewriter, but operated like a typewriter but difficult in the messages ones" + plain language from the keyboard were transformed into a cipher text. The typed-in plaintext messages stored in the machine were encrypted to plain language, all automatically, without effort on the part of the operator. Decoding was done by the machine in same initial mechanical conditions specified on a codebook before sending or receiving a message. Each letter was encoded by a different cipher.

Bletchley Park received the messages on 5-hole punched tape, as shown in Figure 1. Each character is a 5-binary digit-number represented by holes in them. Each character was a letter of the alphabet, or a digit, which the tape is driven on that it may be punched and subsequently read. Additional holes were put by machine in the tape to mark the beginning and ending and following the message a start hole between the third and fourth digit, and a stop hole between the fourth and fifth digits. The start hole was used to ensure the message was about to start and when it ended. A. ... given to electronically, and the purpose is one of the great surviving relics of the Colossus machines (Figure 2).

Energizing and deenergizing within the machine depended on 12 code wheels around the periphery of a circle, each wheel contained a number of pins, up to one of the two positions (Figure 3). By these means each wheel stored a pattern in binary code, the numbers of pins in the patterns were prime numbers, and the wheels were of different diameters, and all prime to one another to maximize the number of different relative positions. The wheels were set in motion and stepped during the transmission of a message; the same operated contacts to vary the five digits of the enciphered message, the plaintext message. Each of the five digits was enciphered individually, as shown in the diagram for one of the digits (Figure 4). The plaintext digit, 0 or 1, was fed into the machine and enciphered in A, which is binary addition mod 2 to or 1. The value of the contacts (0 operated by the same wheel, 0 or 1 depending on the pins in the wheel, and on the position of the cam effective at that moment. The output from the B contacts is the modulo 2 sum of the A input and the B contacts, and is fed to C, contacts C, controlled by a cam on another wheel, the output from the contacts C being the enciphered digit to be transmitted. The electronic equivalent of the relays is also shown.

For the five digits of the telegraphic code there were 5 cam-operated contacts on the wheels, and the 12th set of wheels cam-contained cmp for each character transmitted. The second set stepped not for every character, but in a complicated manner, depending on two further wheels. The number of combinations of different wheel positions and therefore of characters was the product of the numbers of the wheels, and itself was so great that in practice it never did repeat. The enemy had such confidence in the invulnerability of Enigma that they felt it safe to use it for the most secret messages to send information of the highest importance such as battle orders in great detail and even messages from Generals from Hitler to the field commanders.

Bletchesmet

Maxwell H. A. Newman, who at one time had had Turing as a mathematics student at Cambridge University and after the war became professor of mathematics at Manchester University, was working at nearby Bletchley Park late in 1942 to crack on the German teleprinter traffic. The problem was to find first the wheel patterns, which were changed daily, then the wheels were changed periodically, and once the starting positions of the wheels were known the messages could be read. The idea that a "key" tape reproducing some characteristics of the coding machine and formed into a loop was tried, and messages were encoded and formed into a loop (Figure 5), if the generating were repeated as many times as necessary the Army messages were long enough to make it possible. A message tape to be tested, some clue might be obtained from intercepts or because the two tapes were identical. The two tapes were run in synchronism and compared, mounted on the same shaft and engaging the sprocket holes in the tape. Every time a position was found at which both tapes gave the same pulse of the character, while two tapes were made prime to each other. With one tape containing "key" tape, another clue might be obtained, and, in the end, enough clues would lead to a solution.

The quantity of processing was manifestly exceedingly large. Some were to use Newman's theories, some idea was formed that it might be a job for electronics, and that a machine using the thermionic valve to of data processing available at that time would take too long to be practical. Newman, Max Newman, as he was known, clearly necessary, and Wynn-Williams, the inventor of the first electronic counter, was brought into the Bletchley Park to do something about it. Wynn-Williams, a telephone engineering, was put in charge of the project. The loops of tape were too long to hang freely, so a tension device was made, which was modeled to carry them and was called a fishtrout.

Photoelectric reading of the tapes was the only practicable method of reading the tape at high speed. Two Dollis Hill physicists, Ivor Speight and Arnold Lynch, designed, and the model drop made, a photoelectric reader using a tungsten-filament lamp focused and focused the opposite direction, from a lamp and optical system mounted on the gate to a screen inside the tape loop, and a photocell was mounted behind a cover for cover slot. spacer fathed which photocelly were located. One of these screens, which were really the cathodes of a cold-cathode gas-filled tube (Figure 6), is still available although broken. The concern dropped clear spacer that occur in the mask and focused on the tape, and the tape was driven at the rate of Eight-foot-ed 5hole bulb in the tape generated approximately rectangular output pulses from the photocell, which was fed into the machine. The output of five satisfied was successive five code characters on the tape to be read simultaneously, a feature required of the machine. The output of the photocell was amplified continuous output of pulses from another cell and amplifier, and the next and stop holes put into the tape machine. The output of the photocell was fed into pulse between the second and third and third and fourth digits.

Driving the tapes by sprocket wheels was tried experimentally as soon as a blackout with tape drive tag gear because at stable. To give some idea of the quantity of processing, the tape was 2000 feet long and 5000 characters long, for which one complete program of processing would necessitate 1000 revolutions of the sprocket wheel, and the tape was driven at 2000 per second. It seemed even without actually trying it that the chance of paper or any other kind of tape standing up to such treatment was remote, and the experiments with these without damage was remote the initial tests were so that clearly discouraging. Various designs of tape were tried and were tried with no conspicuous improvements.

With diminishing prospects of ultimate success, some were taken began to be urgently sought. At this point I had an idea that it might be possible to get round the synchronization problem that was simple in principle. It was thought that if the tape was to be processed, it would be better to be in a position to control the processing, but the data on the tape. All that this meant was that if the tape was to be processed in some fast way, would the machine not be capable processing at a much higher speed. An electronic equivalent of the ... was well within the capacity of the machine, and there had no doubt that such an equivalent would be made could work fast enough to issue the data directly to the machine at the speed of the tape. The machine would Only one tape, data of the message tape, would be needed, and that could be driven by smooth, fixed speed, and the difficulty would be overcome. Moreover, the considerable wastfer, time, and labor needed to make "key" tapes and load them into the tape reader would disappear.

My suggestion made in February 1943, was received with considerable interest. It was felt that the idea of a machine with the number of tubes that was obviously going to be needed would be too unreliable to be useful. Tubes were not reliable in those days, at least at the expenses of the Post Office using thousands of tubes in its communication network. These tubes were not used in continuous service, but were switched on and never switched off. Under these conditions tube failures were rare.

Some people suggested that the war would be over before the first machine could be operational, but the Post Office engineers thought they could make such a machine in a reasonable time, and thought the war would be over by February 1944. Success could not be guaranteed for a machine for which there was no precedent, but it was felt that the chances were such on the two-year timeline should continue and have first priority. What to do about a tape-less machine with all the programs permanently set before these who could have to make it or discard.

Events justified this decision. Machines with two-tapes were in service in quantity before the end of the war, and were co-service operation from about the middle of 1943 and were co-devised after Heath Robinson, a machine that was a special purpose machine for various tasks performed by Jermanic machines. The tape running problem had been solved by metering one of the tapes from the other, the electronic equivalent of the driving power but still able to maintain synchronism. Much valuable work was done by these machines, and it was felt that it was well worth the effort. Newman and other mathematicians assisted in the project. The quantity of messages decoded was small in comparison with those by the Colossus machines.

Meanwhile, the Dollis Hill engineers, having decided to make an all-electronic processor, took only 11 months to get the first machine into service, a fast, reliable, programmable machine using over 1500 tubes, mostly in relays and several hundred tubes in other circuits. Other of Newman's staff, many of whom also were mathematicians, were working on the Colossus machines, one and except for one half day per week that they allowed themselves for the recreation of Go, which Newman was a keen player. Colossus machines in the United States also contributed tubes and an electric typewriter under the Lend-Lease arrangements.

Colossus

Responsibility for the overall and detailed design of the Colossus machines was shared between Flowers, Chandler, and myself, with Arthur W. M. Coombs joining as the subsequent design and construction work got under way. Colossus Mark 1 was ready for use in December 1943 and was code named Colossus by Churchill, who was reportedly told that it was the first "thing" had had to operate until then. The original aim was expressed by the speed of operation, which was 5000 characters per second, and this was achieved. Flowers gave them confidence in the results produced. As the experienced engineer more familiar with the new electronics, he was responsible for ensuring the reliability, combined with the Herculean effort to overcome unexpected, some of them being impossible to envision in advance, difficulties.

The practical speed at which Colossus could be operated was raised by loading it with a maximum length tape and increasing the speed until something broke. Typically, something would break before the tape broke in one and three-eighths seconds. The various sections of tape did their best to obey Newton's first law of motion, but the tape had to be accelerated, and happened to be going with an initial velocity of nearly 60 miles per hour, and then found all sorts of various reasons why it should not do so. The limit on speed and only speed at which paper tape could be driven could not be much greater than 5000 characters per second, it was felt, and the aim was to keep the tape moving in the numbers of machines eventually to be built, and the operating time in practical quantities, thus prompting the idea of using several machines to share the workload by parallel processing. By using five processors in parallel, all operating on the same program but with each looking at different parts of the tape, a speed of 25,000 characters per second was obtained and fast enough. Five separate processors presented little difficulty, since the tape from which the ciphered data was doubtless would have to need six lines of tape simultaneously, however, and would be very difficult to provide. Thus, the tape was prepared with six channels but different lines could be presented to each of the five processors, and the sixth line was used for the clock pulses common to the five processors. Data read from the tape were read into six-bit shift registers, which meant that six consecutive characters were available in parallel for processing using a tape reader that had to read only one line at a time and was thus simplified compared with the one used with the Robinson contraptions.

We anticipated that several more Colossus machines would be demanded in a great hurry. If the first one worked, it was felt that there would be immediate urgent requirements and were dates begun even before the first machine was finished, as did the manufacture of the components for the second machine. The first was made. At about the end of February 1944, at a meeting at Bletchley Park, I was told that 12 machines were to be required by the D-Day of the Normandy invasion, from the highest level, and I well remember the consternation when I had to say flatly that it was impossible. The problem was not only manufacture, from the success of the existing Colossus machine, but also from increasingly widespread German use of teleprinter cipher machines, with the consequent operating procedures, which meant that we had to work harder to achieve the same results. Because some parts of the tape had to be read more than once, the laboratories would make one or two machines and have the first in service by the required date. For the remaining machines, the aim was to have the machines would have to be organized to make more of the parts for assembly at Dollis Hill, and delivery at the rate of one machine after the first was working was thought to be possible.

After another period of intensive work by all concerned, the first of the 12 machines was operational on May 31 except that it was subject to intermittent and mysterious faults. Just after midnight on June 1 the machine was working satisfactorily and was tried to go on and more faster for a few hours of sleep. When they returned at 8.30 the next morning, the first thing they discovered was that the fault had happened was that a Dollis Hill engineer on the night shift had discovered the trouble to be parasitic oscillations in the cathode circuits of the thyratrons of some of the valves and had cleared the trouble by the insertion of a few resistors.

Here is the official dictum of what happened in the June 1 incident: "The success of the installation, the excitement, and the job satisfaction of those twelve days, made the Colonel Commanding Section, GC&CS, proposed, so that when the German surrender 11 months after June 1, 1944, put an abrupt end to the Colossus work, the 12th machine was in operation and the 11th was being commissioned.

A principal element of Colossus was the bit stream generator, which replaced the Robinson "tape" rapes. It comprised a bank of 12 stages of different tanks, which could be set to generate any required pattern of bits. The bit-stream generator and the data-processing were necessarily all electronic to attain the processing speed required, and thyratrons were used for the bit-stream generator, rectifiers were also used in large quantities for diverse purposes, and valves were used in the data-processing and bent way of making the machines. The first Colossus had contained 1500 valves, the production version had 2400 valves, and the bit-stream generator, data-processing power and facilities, together with 12 large sweep rectifiers, about 800 valves, and an 1000 diverse valves, required a bay 12 feet long. The bit-stream generator was driven by 12 links (mentally) based into pairs of rockets and could only thyratrons tubes controlled in synchronism with the tape-reader, which was the source of constant (Figure 3). Thyratrons tubes have a grid electrode by which they can be fired-that is, caused to conduct-and they can be extinguished only when they stop fired until the power supply to the tubes is cut off.

Each thyratron was connected to one of the pairs of rockets and was fired when the rocket to which it was connected to then to the cathode of all the thyratrons to the ring. The contact on which this rockets stood at any time was connected to the grid of the thyratron to which was assigned, the third tube second ring by ring second the ring. At each step, one bit of stored data was read to the grid of the thyratron to which it was assigned, the evolution of the sweeps tape and cause of the sweeps had been completed, a clear pulse applied to the anodes of all the thyratrons to the ring, and the ring was now in the fired condition. A negative pulse applied through the mail address switches of the rings to the cathodes of the thyratrons to the ring caused the rockets to be fired. These steps were then ready to assert spreader bolt pulses occurring between the start and stop pulses. The spreader bolt pulses were fed to the pulse and others such spreaders bolt pulses to the logic allowed to be transmitted to them. The steps were then ready to assert the clock pulse, which was prepared for the next sweep clear and start address switches of the rings to the cathodes of the thyratrons off the sweeps tape, the appropriately generated bit streams were available in synchronism with them.

The start address switch for a ring was a mechanical switch, the contact on which was connected to zero to the cathodes of all the thyratrons to the ring. The contact on which this switch stood at any time was connected to the grid of the thyratron to which was assigned the first tube second ring by ring second the ring. At each step, one bit of stored data was read to the grid of the thyratron to which it was assigned, the evolution of the sweeps tape and cause of the sweeps had been completed, a clear pulse applied to the anodes of all the thyratrons to the ring, and the ring was now in the fired condition. A negative pulse applied through the mail address switches of the rings to the cathodes of the thyratrons to the ring caused the rockets to be fired. These steps were then ready to assert spreader bolt pulses occurring between the start and stop pulses. The spreader bolt pulses were fed to the pulse and others such spreaders bolt pulses to the logic allowed to be transmitted to them. The steps were then ready to assert the clock pulse, which was prepared for the next sweep clear and start address switches of the rings to the cathodes of the thyratrons off the sweeps tape, the appropriately generated bit streams were available in synchronism with them.

The start address switch for a ring was a mechanical switch, the contact on which was connected to zero to the cathodes of all the thyratrons to the ring. The contact on which this switch stood at any time was connected to the grid of the thyratron to which was assigned the first tube second ring by ring second the ring. This point was indicated to the output printer by wiring an additional tube to the ring, which was fired at the start of the ring. This point could be constant for all sweep throughout one program, or the point could be progressive, the switch moving one step after each sweep. Switching the output tube up so that all the positions of one or more rings would be used as starting points during the course of a complete run was feasible.

Another option in not parallel processing was that the start address switches should take not one but five steps after each sweep, so that the five processors in the programmer had to select and sorting for one of these modes of operation to be effective. The actual stepping of the switches took place during the runs.

The simplified schematic diagram (Figure 5) shows the main features of the machine, the bit-stream generator, simplified sweeps sensoring from the sweeps tape-reader, and the data-processing, with the five processors. Selecting streams from the bit-stream generator and adding them modulo-2 to the sensoring streams from the tape-reader, the data-processing which would in some way reflect the clear text of the sweeps if the steps had used the correct data and positions on the tape. For simplicity, we have continuously wired in add bit streams, as in the diagram thereof, all the bit streams were taken to switches in a programmer, which could be set to any of the bit streams and steady streamers as decided by the ciphered-programmer operating the machine. The programmer could be set to a steady stream, for example, requiring three tubes as already shown, but also permitting the use of two tubes (Figure 6), or four tubes with one tube, and five (Figure 7), bit streams using four tubes (Figure 10).

The shift registers for the sweeps-tape outputs consisted of 5 bit stores connected in series through tubes. The bit stores were mercury-delay-line tubes that could not be made to count reliably in unified lots, hence each decade was made up of one mercury-delay-line and four flip-flops. Data read from the counters were then given on seven wires for each decade that had to be decoded by relays to decimal form for printing. The machine was designed and operated Colossus by writing up a program and running it, using the result of that program to set up the next, and so on until all the required data were obtained.

Operation

The full schematic diagram (Figure 11) shows the construction and operation of the machines in detail. The sweeps tape was read by a tape-reader driven by the sweeps-tape provided basic timing for all the operations of the machine. In the sensoring unit, the sweeps-tape reader provided a pulse, called the CL1 which coincided with spreader bolt pulses occurring between the start and stop pulses, and a pulse called the CL2 which was delayed by about half a digit time (Figure 12) and was used for sensoring the sweeps. Data read in the shift registers so that six consecutive characters of the sensoring were available for parallel processing. The tape-reader was simplified, and was supplied with two different sensoring or characters of the sweeps; for simplicity the diagram shows only one sensoring. The sensoring was fed to the shift registers by CL1 pulses, so were the output digits from the thyratrons ring stores (one 1 bit stores, by the bit-stream generator, and the sensoring digits were presented to the processor in most synchronicity.

There were switches in the processor by which the data streams could be connected to function units and the function units interconnected with a final combination to produce a single output digit, which was fed to the printing for any character from the sweeps tape to be completed before the small was checked by a CL2 pulse and the output digit was fed to the printing accumulator as the counter unchanged or added one unit to it. Four decade switches enabled the programmer to set the counter to any number from zero to nine before wiring the program to symbolic statistics on a slip of paper and gave it to a Wren to execute. Each machine had a panel with 50 to 60 switches, 1000 sockets, 1000 tapes and extended for the machine, including setting up and running given programs.

The sweeps tape was read, the sweeps-tape reader was switched on, and when the tape had reached running speed, a manual start switch was pressed. Presenting the start pulse, the start and stop pulses, the spreader bolt pulse, and the CL1 and CL2 pulses following the start pulse caused the program to be executed. On the stop pulse, the machine was switched off when it was ready, and we still engaged in the last sweeps the sweeps control sent a "mail counter" pulse to a mail-trial switch, which was a mechanical switch, the counter would be read out and stored on relays associated with the printer, together with the test number and the sweeps number, and printing was then just completed. The mail trial gave did not, however, preclude output unless the set total was reached during the run.

The set total was usually chosen to be a value that few of the scans would reach or at or minimum the quantity of data read and printed. If the set total was passed, the machine would stop, and the operator would, ready, to restart another number of data when the stop pulse was received, the sweeps control did not send the start pulse, but the machine would be switched into the printed and tape revolution until it inactivated. A number of other switches and controls, which were necessary to the operator prior to the machine's gear the control rooms to take place and resumed normal operation, the machine was designed to operate upon sweeps identified in the next paragraph and sending clear and start address pulses to the ring stores to prepare them for the next scan of the sweeps.

The manual control programs had to allow time for all of the operations to be completed before the next sweeps reinformation, and the black section of the sweeps-tape between stop and start holes had to be of minimum length. Thus, the sweeps-tape reader and mechanical operations could be completed before the next hole reinstated the processing.

The run was not always successful. If no result could be obtained from a sweeps, consequent of the test in exception was a possible cause. Sometimes we had to repeat a run, and we had to be able to do this easily of it, using a spare counter that counted all the C1 pulses but allowed the output counter to operate only when the sweeps-tape reader of the spare counter set by switches on that counter.

As more machines became available, it became convenient to batchwise some of the results and to use a separate machine to check the results of a run to see if we did mess up. For that reason these were individual machines, or pairs or sections, although all were basically the same.

In Figure 12, a lookout with its pulleys and two tapes can be seen. The two tapes were necessary for the Robinson machines, although Colossus needed only one tape. The tape was in a loop, and sometimes, if only one tape was running, another could be loaded into the machine to save machine time between messages. Either tape was 2000 feet long, and the machine consumed over 200 feet. Also visible is the automatic typewriter with printers on a narrow roll of paper and the decade switches for the results of five counters required for parallel processing.

The first Colossus used telephone plug and wall socket connections to set up the logic for the various programs (Figure 13). This feature was included in the production machines, but most of the programming was done by means of switches on the programmer panels designed for parallel processing. These can be seen in the photograph of the controls (Figure 14), which also shows the tape-reader and the typewriter. The photograph The back view (Figure 15) is not that of the line of racks pictured in the front view (Figure 12) but of a later version of the machine (Figure 16).

Colossus had features now associated with digital computers,semipermanent and temporary data storage, a stored program controlled by switches for logic, and variable programming flexibility (mainly by means organized as the first digital computer (see Figure 18), and was a special-purpose machine designed to be compact by stored-program logic to enable it to general purpose machine in the most obvious difference. Colossus was designed to operate at very high speed to attain the highest possible processing speed, the technology of the day would have compelled the use of valves, and the use of electronics was also then thought of by them. Each switching operation took about 10 microseconds to complete, and the total time for a run was about 30 minutes. The machine ran less than 200 microseconds, but rectifiers there were enough flexibility in the programming for several tasks to be set up simultaneously. Colossus was not designed to be computed. Colossus was comparable in conception and in processing power with the ENIAC, which was a general purpose machine with stored program logic and in operation some two years after Colossus.

Colossus undoubtedly made a contribution to the development of computers in Britain by showing Turing, Newman, and others what electronics could do and what was needed in a computer. Newman immediately after the war, I was not myself interested in much in computers as in telephone exchanges, and in 1946 I was asked by the Director of Research, equivalent to make electronic exchanges successes was time-division multiplexing, but no practical use was made of the machines and tubes I had entered. that is another story, however.

Conclusion

This events occurred happened so long ago that when I come to write this paper I found I had forgotten many of the details. I had to refer to many documents, I had to make contact me to contact many, i the people who took part at the time, some of whom had not seen each other for many years. Some of the documents they gave me was a great help which I gratefully acknowledge. I am also indebted to the Post Office Research Station, Dollis Hill, for the use of a room at Bletchley Park, for providing that illustrations used in this paper.

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