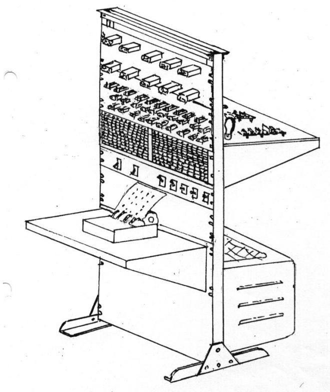
The rebuilding of Heath Robinson.

By Tony Sale

1. The original Heath Robinson.

Heath Robinson was the first attempt to use a machine to help in the breaking of the German Lorenz ciphered teleprinter traffic in WW II. It was Max Newman's idea to try a machine attack and Heath Robinson was designed at the Telecommunications Research Establishment (TRE) by C. E. Wynn-Williams, who had already been involved with Bletchley Park in the design of a high speed Bombe for breaking German Naval Enigma traffic. It was very much an experimental machine and was called "Heath Robinson" after the WW II cartoonist who pictured fantastic machines, Rube Goldberg was the American equivalent.



Original Heath Robinson Rack
as remembered

Harry Fensom
18-6-99

2. The Lorenz problem.

The German Lorenz machine was used to encipher teleprinter traffic between command centres of the German Army. The cipher used the Additive method invented in 1918 by Gilbert Vernam in America. This method involved adding together the teleprinter code bit patterns, bit by bit, of the input text character and an obscuring character generated by the Lorenz machine, giving the transmitted cipher character. When this addition was performed binary modulo two (XOR), at the receiving end the same obscuring character regenerated by the receiving Lorenz machine, added to the received cipher character cancelled out the original obscuring character and revealed the original text character.

In fact the Lorenz machine generated and added successively two obscuring characters from two sets of five wheels known as Chi and Psi in Bletchley Park. The Chi wheels incremented regularly every time a text character was entered, the Psi wheels incremented erratically, but as a group of five, depending on two other wheels known in the Park as Motor or Mu wheels.

This had all been deduced by John Tiltman, Bill Tutte and others by early 1942. There were two parts to the solution of Lorenz. Firstly to work out the patterns around the periphery of each wheel and secondly to determine the wheel pattern start position for each wheel.

Chi wheel patterns starting at position 1 on the Chi wheels

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Chi1 ..xxxx.xx....xxx..x.x...x.xxxx.x.xxx...x.|
Chi2 ..xx.xx..x..xx..xxxx.x...xxx..x|
Chi3 .xx.xx..xx...xx...xxx.x..xx..|
Chi4 ..x....xxx.xx..xxxx..x..xx|
Chi5 ..x.x..x.xxxx....xx..xx|
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Chi wheels turned to 32,2,2,16,2

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Chi1 x .xxx...x.|..xxxx.xx....xxx..x.x...x.xxxx."
Chi2 . xx.xx..x..xx..xxxx.x...xxx..x|."
Chi3 x x.xx..xx...xx...xxx.x..xx..|."
Chi4 x xxx..x..xx|..x....xxx.xx.."
Chi5 . x.x..x.xxxx....xx..xx|."
     F VJXU4O9QO
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The Chi stream obscuring characters generated as the wheels turned for each text character typed in.

The same wheel patterns were found to be set over various periods and over many messages but the wheel pattern start positions were changed for every message and just for the Chi wheels this gave a 22,000,000 combination.

3. Finding the Chi wheel pattern start positions.

At Bletchley Park, Bill Tutte had proposed the "Double Delta" method for finding the Lorenz machine wheel start positions to which the German operator had set his Lorenz machine. (different wheel start positions for each message).

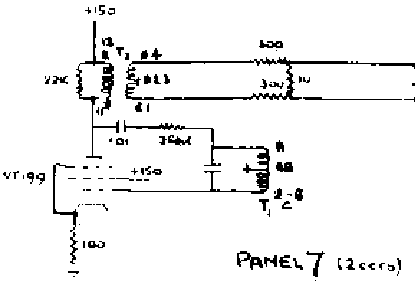
The Tutte algorithm required adding modulo two (XORing) the current and previous character bits on both the cipher text (Z) and the Chi wheel patterns (X) being tested to get the Deltas and then XORing these together for two of the five channels (tracks) on the paper tape and counting, down the whole length of the tape the number of times that this result equated zero, trying various pattern start positions to find the maximum score.

i.e. if channels 1 and 2 are being used then count when;

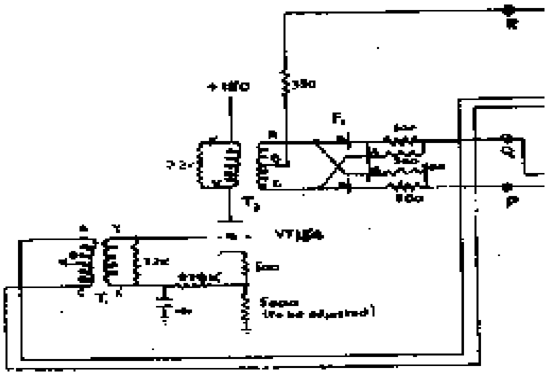
DeltaZ1 + DeltaX1 + DeltaZ2 + DeltaX2 = 0

4. The Wynn-Williams proposal.

When Wynn-Williams was asked to produce electronic circuits to implement the double delta algorithm he chose to use a phase modulated carrier from a master oscillator at 25kc/s to perform the XOR logic.



He decided to use 0 and 180 degrees of phase to represent 0 and 1. The elegance of this is that if a "1" causes 180 degrees phase shift, then another 1 returns the phase to zero and thus this implements an XOR function (0 + 0 = 0, 1 + 1 = 0, 0 + 1 = 1, 1 + 0 = 1).

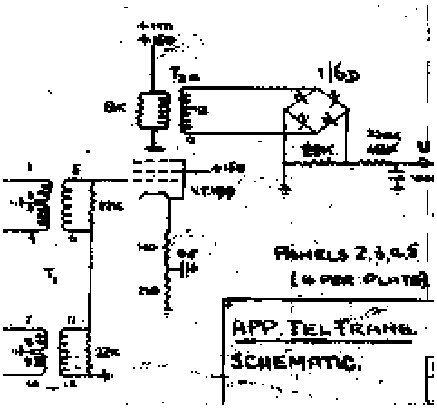


PANELS 10,11,12,13
(4 PER PLATE)

The 180 degrees phase shift was achieved via a diode bridge circuit and a balanced transformer. The biasing of the bridge, + - 10 volts, determined whether the input carrier went straight through (no phase change) of shifted 180 degrees.

A triode valve amplifier was included with each bridge circuit to compensate for the losses in the bridge and to give unity gain from input to output.

The output phase at the end of a series of logic circuits was compared with the phase input to the logic circuits in a detector circuit. This gave a voltage output of nearly zero if the input and output are in anti phase or some, much larger, positive voltage if they were in phase.



The output voltage from the detector was sampled by a pulse derived from the sprocket hole signal from the tape reader. The result of this sampling, either a pulse if the detector output was positive, or no pulse if the output was zero was then passed to the decade counters to accumulate a count down the whole length of the tapes.

There were four decimal decade counters in series giving a 9999 maximum count. The first stage of the decade counters consisted of a ring of ten thyratrons (gas filled thermionic triode valves). The circuit for this was designed by Wynn-Williams before the war for counting in nuclear particle experiments.

A thyratron valve will strike and hold an internal arc discharge when there is a positive voltage on its anode and the grid voltage is raised towards the cathode voltage allowing current to start flowing. Once the discharge is started the grid voltage has no further influence over the anode current. Thus the thyratron "remembers" it has been struck and thus acts as a one bit store. Unfortunately the only way to stop the discharge in a thyratron is to drive the anode negative with respect to its cathode.

In the decade thyratron ring the thyratron which had been struck had to prepare the next thyratron in the ring to be struck on the next input pulse, but at the same time the next thyratron struck had to cause the pervious thyratron to be extinguished. In the Wynn-Williams circuit this was achieved by coupling successive thyratron's cathodes together with a large capacitor.

The thyratron ring was the fast, least significant, decimal counter. The next two counters, the tens and hundreds, used high speed relays with slow speed relays in the thousands counter. The count was displayed on a lamp panel.

There were four sets of counters, each of 9999 capacity. The output from the logic circuits was switched alternately into one of two counter sets, the changeover occurring at the end of reading the data on the two tapes. Each tape were joined end to end in a continuous loop. Special holes were punched into the tapes to signify end of data and start of data.

The remaining two counters sets were used to count sprocket holes. These counts allowed the calculation of Chi wheel positions for a particular score.

Initially all counts had to be read off the lamp panel and written down, a great source of error. Later a special printer known as a "Gifford" printer was added. This was not a great success.

Heath Robinson consisted of three parts, the frame on which the teleprinter paper tapes were mounted and read optically, known as the Bedstead, a wide short rack containing the counters, a lamp output panel and later the Gifford printer on a front table, and a tall 19 inch rack known as the valve rack which contained the logic circuits and a jack field panel for plugging up the algorithms.

The short counters rack was produced at TRE and the Bedstead and valve rack at the GPO research labs at Dollis Hill to Wynn-Williams circuit designs.

The cover name for the project was "Apparatus Telegraph Transmitting", case number 11951. The Bedstead was designed by Arnold Lynch and Eric Speight.

Harry Fensom and Alan Bruce worked on commissioning the system at Dollis Hill.

There were difficulties in getting the ring modulator logic to work due to extra phase shifts in the circuits when more than six circuits were connected together one after the other. Allen Coombs relates this problem and tells how he went to Tommy Flowers for advice. Tommy Flowers said "change the frequency" which Allen Coombs did. It solved the problem but neither he nor Tommy Flowers knew why.

Eventually it all worked together and Heath Robinson was moved to Bletchley Park.

5. Heath Robinson at Bletchley Park.

Heath Robinson was delivered to Bletchley Park in June 1943 and was first installed in Hut 11 which had been the original Bombe room for Turing Bombes, the machines used to break Enigma.

Harry Fensom and Alan Bruce were the two GPO maintenance engineers assigned to Heath Robinson. Two WRNS(Womens Royal Naval Service) ladies at a time were the operators and Jack Good and Donald Michie were the code breakers.

The first problem was teleprinter tape preparation. At least 2000 characters of cipher text was required, joined end to end to make a continuous loop. Then a similar length of Chi wheel patterns had to be punched up and arranged to be just one character longer than the cipher tape. This was to automatically change the relative wheel patterns by one position after each complete run through the tapes.

Then it was found that the optical readers in the Bedstead gave errors if a long stretch of adjacent holes or no holes occurred on the tapes. This meant adjustments to both texts to compensate for this.

A major problem was keeping the two tapes in synchronism at over 1000 characters per second. Originally the sprocket drive cogs were motorised but this proved impossible to sustain without tearing the tapes and a friction drive was used from the paper tape pulleys with the sprocket shaft just idling to keep synchronisation. This proved to be better but there was still a problem with tape stretching in the distance between the sprocket cogs and the optical reader aperture.

But Heath Robinson was the first machine to be used to assist in breaking Lorenz and despite all its problems and limitations it worked well enough to more clearly define the specification of an improved machine and this led to Colossus, but that's another story.

6. The Rebuild of Heath Robinson.

By the year 2000 I had spent seven years rebuilding Colossus, which although still not complete, had demonstrated the enormous code breaking power of a dedicated electronic computer. In 2000 I was banned from Bletchley Park by the Bletchley Park Trust for opposing the demolition, by the Trust, of wartime C Block, the Freebornery, a massive punched card installation essential to the Enigma code breaking work.
This meant I could no longer work on my rebuild of Colossus and my thoughts turned to Heath Robinson. I had always been intrigued by its rather esoteric logic design and decided to try to recreate it to see how it really worked.

The first problem encountered was lack of any photographs of wartime Heath Robinson. It was briefly described in a paper by Allen Coombs in the 1983 edition of the Annals of the History of Computing with a fragment of a circuit diagram but no layout or visual description. This paper described the 25Kc/s phase modulated method used in the logic circuits.

In 1996 Harry Fensom and I had visited Allen Coombs at his house just outside Plymouth. Harry, who was a GPO engineer at Dollis Hill, had worked on Heath Robinson and then on the Mk 1 and Mk 2 Colossi. Allen Coombs had had a slight stoke and could not communicate very well but he gave me all his wartime notes which he had kept, quite illegally, after the war. I promised to be discreet in my use of these notes. We did not discuss Heath Robinson with him. I was then deeply involved in setting up and running the Colossus Rebuild Project for which his notes and circuit drawing fragments were a great help.

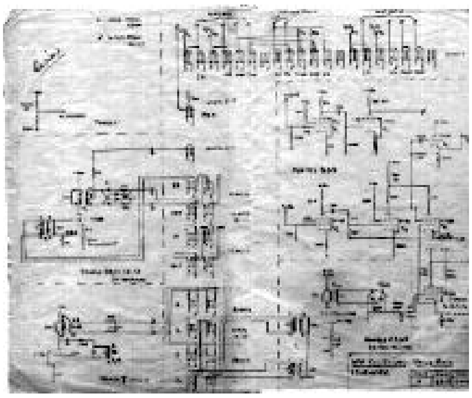
In 2000, on looking back again through Allen Coombs's papers I suddenly realised that one A3 sized sheet was in fact circuits of Heath Robinson, recognisable by the ring modulator circuits. On checking back to Allen Coombs's paper of 1983, it was clear that the parts of circuitry in the paper had been copied from this original sheet.

There was also, next to it, a machine drawing of a 19 inch plate with a rectangular aperture in it. This machine drawing had the title "Apparatus Telegraph Transmitting", case number 11951. I had already identified this title, confirmed by

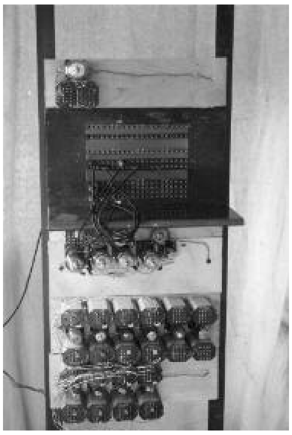
Arnold Lynch, as being used for the Bedstead design. When I was building the Colossus bedstead in 1994 I had searched the BT (Ex Post Office) document archives. Cases 11950 and 11952 existed. No trace of 11951. Confirmation of secrecy?

In 2000 I first put together in best birds nest style a lashup of the 25kc/s master oscillator and two bridge logic circuits. I had to design the transformers for these circuits from scratch. No such details on the surviving circuit diagram. However I reasoned that if the circuits were wired up at Dollis Hill they probably used standard GPO components and the transformers in Amp 32 units seemed likely candidates. I had collected lots of these to obtain surface mounting valve bases for Colossus so I stripped out some transformers from the Amp 32's and then took the transformers to pieces, removed the wiring and rewound them to work at 25kc/s. I hadn't lost my transformer design skills and the lashup worked well showing the 180 degree phase shift as the bridge bias was altered. So I had shown that it was possible to recreate the Heath Robinson circuitry.

There the matter rested until in May 2001, still being prevented by the Bletchley Park Trust from completing my Colossus, I decided to completely rebuild Heath Robinson.



I first studied in great detail the A3 sized circuit diagram of Heath Robinson. A considerable amount of information could be deduced from it. Firstly the number of Post Office jack strips referenced on the circuit page corresponded exactly to the aperture in the drawing of the 19 inch plate. So this was a jack field of 20 way jack strips. But this implied a 19 inch rack whereas up until then I had assumed that the only rack was the wide not very tall main Heath Robinson rack built at TRE. However talking to Harry Fensom, he confirmed that the "Valve Rack" had been built at Dollis Hill and was a tall 19 inch rack. Furthermore the words for chunks of circuitry on the circuit diagram were "plates" and "panels" confirming Dollis Hill origins. (TRE would have called them "chassis"). So now there were 13 plates of which by inference the jack field was number 6.



Next what size were the plates. I was pretty certain, and Harry Fensom confirmed, that the standard GPO transformer cases were used as in Amp 32's. This allowed 6 transformers side by side long ways across a 19 inch plate. So the 12 transformers required for the six logic circuits per plate implied two rows of six transformers with the valves centrally in a row between each transformer pair. This gave a plate width of 6 inches. Now with a slightly narrower plate for the master oscillator, all the plates fitted onto a Colossus rack height of 90 inches.(Harry confirmed that they only used one rack height for all machines.)

There were two transformer types on an Amp 32, one with a large bobbin and laminated core, the other much smaller. Which to use? I noticed that on the circuit for the detector, transformer labelled T1 contained two cores.

That confirmed that the smaller cores were used since two small cores would fit into one transformer can.

So now I revisited the design of the transformers based on the small bobbin and laminated core. Again my old design skills didn't fail me and the resultant transformer at 25kc/s had zero phase shift input to output, almost zero leakage inductance and only loaded 600 ohms by 10% with open secondary.

I decide to use plywood for the plates to avoid cutting steel until I was sure of the layouts. When I mentioned this to Harry Fensom I was pleased and relieved when he said that that was exactly what they had done at Dollis Hill. So I built a plate for the master oscillator, two plates each containing four logic gates and a detector board. All using the rewound transformers and with extra components like the bridges inside the transformer cans.

A test of eight logic circuits in series showed that nearly zero unwanted phase shift could be achieved with the addition of a capacitor and a damping resistor across the anode coil of the output coupling transformer in each logic circuit.

Next problem, how to simulate the tape reader bedstead before actually building one. I realised that I could use the line printer parallel port on a PC as a signal source. Eight data bits would give me the signals as if coming from eight photo cells, i.e. previous and current bits from cipher and Chi tapes for two tracks out of the five on the tapes. The strobe bit on the LP port could simulate the sprocket pulse. A quickly written Qbasic program gave the right information written to the LP port but the output lines were switched between 0 and +5volts. A rapidly wired interface box using Op Amp chips produced the +- 10 volts required to drive the ring modulator logic circuits.

A few delay loops in the Qbasic program allowed the data rate to be set and ensured that the simulated sprocket pulse arrived correctly in relation to the changing logic drive signals. I had also wired up parts of the jack field panel so now the whole circuitry could be tested from paper tape signals to detected output from the double delta algorithm and it worked extremely well up to a simulated data rate of 2kc/s.

Because I was using in my Qbasic tape simulation program the same cipher text and Chi patterns as in my Virtual Colossus, I could do a direct comparison of results from the double delta algorithm. They were exactly the same on Heath Robinson as on Colossus.

Now came the counter circuits. No circuits for these but Harry had told me that a ring of ten thyratrons had been used. I knew Wynn-Williams had worked before the war on counting circuits for nuclear experiments. I looked up his papers in the Proceedings of the Royal Society and found the circuit for a thyratron ring counter. I showed this to Harry who agreed that the Heath Robinson first stages of the counters were like that. So I built them and after some slight experimenting they worked. Now I had to make the relay second and third stages of the counters.

Finally I had to build another Bedstead. I looked back in my Colossus files and re-ordered the necessary steel, since the Heath Robinson bedstead was identical to that used on Colossus.

to be concluded AES 25/06/2001