INTERNATIONAL RESEARCH CONFERENCE ON THE HISTORY OF COMPUTING

LOS ALAMOS: JUNE 1976

Evening Session on COLOSSUS, with A.W.M. Coombs and B. Randell.

(Taped by M. Williams)

Participants (in the order of their contributions)

Randell: Brian Randell (born 1936) is a Professor at the School of Computing Science, Newcastle University, U.K. He is a noted authority on the early history of computers.

Coombs: Allen William Mark (Doc) Coombs (23 October 1911 – 30 January 1995) was a British electronics engineer at the Post Office Research Station, Dollis Hill. He was one of the principal designers of the Mark II or production version of the Colossus machine used at Bletchley Park for codebreaking in World War II, and took over leadership of the project when Tommy Flowers moved on to other projects.

van Wijngaarden: Adriaan "Aad" van Wijngaarden (2 November 1916 – 7 February 1987) was a Dutch mathematician and computer scientist, who is considered by many to have been the founding father of computer science in the Netherlands.

Todd: John Todd (May 16, 1911 – June 21, 2007) was a professor of mathematics and a pioneer in the field of numerical analysis.

Evans: Christopher Riche Evans (29 May 1931 – 10 October 1979) was a British psychologist, computer scientist, and author interested in the history of his subject.

?: Unidentified individuals

Brooks: Fred Brooks is best known for his management of the creation of the IBM's System/360 computers and their operating system and for his book *The Mythical Man-Month: Essays on Software Engineering*

Knuth: Don Knuth is best known as the author of *The Art of Computer Programming*, often referred to by the author's name

Luebbert: Col. William F. Luebbert, from the U.S. Military Academy

Birkhoff: Garett Birkhoff was a member of the the Department of Mathematics at Harvard University

Mauchly: John William Mauchly (August 30, 1907 – January 8, 1980) was an American physicist who, along with J. Presper Eckert, designed ENIAC.

Randell

I have listed here a non-exclusive set of possible topics. What I'll do is read them out and for those that are of most interest then perhaps Doc or I can say a bit more and then just open it up to comments and questions. They are in no particular order.

Topics:

description of and anecdotes about the people involved; circuit techniques; reliability achievements and problems; the design, building and commissioning of the Mark 2; the manufacturing of COLOSSI; the assessment of it as a computer; Alan Turing and thinking machines; the American scene; links to other projects; Flowers' and Broadhurst's post-war careers; the Data Recorder and Mosaic.

That's what I thought up when I got up this morning and scribbled for about five minutes, but I think it will be a very confusing discussion unless we achieve some sort of separation.

Coombs

And there are other things we can talk about;

Randell

Maybe not the others but those are things that I don't feel were covered as well as we might have done yesterday.

?

I think also you can add to that list the effect on the progress of the war.

Coombs

May I step in here? We cannot do this; I don't know why we cannot, but I don't think I can possibly breach any official security if I quote to you - or don't even quote to you - but tell you where you can find it out for yourself in freely published books, freely published and not restricted. I can't tell you but if you buy a book that you can buy anywhere you will know all you want to know about that. I don't see that I can possibly breach secrecy if I tell you that.

Randell

It would be a bit too late.

Coombs

Well anyhow, if you buy a book called *The Ultra Secret* by Winterbotham this will tell you all about how this stuff that we did affected the course of the war, and that book - you will probably not believe a word of it but it's perfectly true - it is not perfectly true it is true to the extent that it needs to be true in the sense that the results given are accurate but some of the details are deliberately confused so that some secrets will not come out, but the answers that are given are correct. *The Ultra Secret* by a chap called Winterbotham who was the administrative controller of the whole scene.

Randell

Well I think I would now like to move on.

van Wijngaarden

To me this is a meaningless statement. Does this mean that how the war was lost by the Germans isn't true? How far can a statement be true without some of the underlying statements not being true?

Coombs

Well, I might say to you, “I went to New York yesterday and I went via San Francisco.” I might say that.

van Wijngaarden

You might say that?

Coombs

I might say, “I went to New York yesterday and I went via San Francisco”. That might not be true. I might have gone to New York yesterday via Washington, but in fact I went to New York yesterday.

van Wijngaarden

That's right.

Coombs

That's what I meant.

Todd

You can give a list of the mathematicians who were there?

Randell

I list some in my paper. I certainly can't list all of them. I don't know all of them. I'll find the list and read it out, shall I? Talking just about the Newman section, the first people to arrive were Donald Michie, who was not a mathematician at that time - he came pretty well straight from school - I.J. Good who was, and the next in approximate order of arrival were Shaun Wylie, J.H.C. Whitehead, Oliver Atkins, Arthur Ashcroft, Gordon Preston, Geoffrey Timms and Joe Gillies, followed after a pause by others.

Evans

Can I ask a question about the selection procedure? This is something that I have always been curious about because Donald Michie told me that it was quite arbitrary, that Max Newman had some hunch that he would just get people who were good at chess or something strange like that. Do you know anything about this? I think they were looking for slightly - I am not doing them an injustice by saying this - slightly freakish people with…

Randell

What I.J. Good has said in open session was that he had the impression that they tended to select people who were good at two things, mathematics and chess, say. Well at least that was what he saw as the criterion that the person who selected him - and the person who selected him was C.H. O'D. Alexander who was, I think, at that time British Chess Champion.

?

Mathematics and chess I suppose are two fairly obvious categories. Were there some more obscure categories?

Evans

They wanted them young, didn't they? That was another thing; they would pick young people where they could.

Randell

For Newman's section basically it was mathematics they were taking for that part of the work. Very obviously they also had Wrens as operators, so there were more people than just mathematicians in Newman's section. The Newman section was just one of the sections. As to whether the other sections had the same sort of selection criteria is not clear.

?

Just going down the topics you've listed - this seems to savour a little of cross- examination and I somehow don't feel that that's the mood that is going to be the most productive and interesting.

Randell

I think probably it would be a good idea if Doc decided upon . . . . .

Coombs

Flowers is a man for whom I have the most tremendous respect. I think he's the best engineer I have ever known. In fact, early in the 1930s Flowers was a telephone engineer and he was designing his circuits using electromagnetic relays which was the process then at the time, using Boolean algebra, but we had never heard of Boolean algebra; we didn't know what it was. He was designing his circuits on the strength of things being on or off and he was doing all that sort of stuff and it was a revelation to us when later on when communications theory came out; Shannon and whatnot, and we realised we had been doing it all the time. Just like Monsieur Jourdans had been talking prose all his life and he didn't know it. We'd been doing it under Flowers' guidance, because Flowers was, really was, a brilliant engineer who saw right through to the real solution of problems. He had done a little bit of valve working on the - he was a switching engineer and I was in the switching division at the Post Office Engineering Research Station - you understand don't you that the Post Office in England, in the United Kingdom, doesn't just do posts, it does telecommunications as well. So it's perhaps a sort of combination between your Post Office Department and Bell Labs as well, on a rather small scale I'd have to admit. Anyway, we were telecommunications engineers. He was in charge of switching and he'd done many, many jobs associated with switching. I had been with him for some time although when all this work started I wasn't working for him. I was in another division concerned more with audio- frequency stuff and low frequency carrier. Well I wasn't in on the beginning of this when he was first called in although your paper is - is everyone going to get a copy of it?

Randell

Nick Metropolis has said that anybody who wishes to should contact him and he'll provide Xerox copies.

Coombs

I've read your paper and it admirably describes how Flowers was first brought into this scene. It was a natural thing to go to in the Post Office when they were interested in teleprinter machines and they came there and we worked on it. Flowers was known as a switching man. But once he got into it with his staff he rapidly discovered that the methods that were being used were not to his mind very sound engineering. With all respect to mathematicians and physicists, and I have a tremendous amount of respect for both of them, when you want a machine which has got to work safely, with a factor of safety, that really is going to go first time and not be mucked about with, I think you've really got to have an engineer on the job, and Flowers had very much the same attitude. Flowers as an engineer came into this project, and once he realised what was happening he said “This is wrong; this isn't the way to do it; you should do it some other way.” Well, he was ignored at first, and this is all in Brian Randell's report, but eventually he was able to persuade the powers that were at that time that his ideas were better and he was allowed to expand them. That's when I was included in the team, though the initial work had been done by then. I was brought into his team on promotion and we got cracking on building these machines and sometime later he was promoted again, to other work, and I took over sole charge of the whole project, and it was the most exhilarating and exciting time of my life. If I did nothing in all my life except what I did for those two years I would feel that my life had been well spent, but it was Flowers who was the brilliant man.

Randell

The next name is Broadhurst.

Coombs

Broadhurst was a man who was a - again described in your piece - he was a man who started work as a railway engineer actually, but then he graduated into the Post Office and became an expert in electromagnetic techniques and relays and things, and he had gone into the training school where his function had been to teach people how to assemble automatic telephone exchanges and how to maintain them, keep them going.

?

Was Broadhurst in the signals section of the railways?

Coombs

Signals section in the railway?

Randell

An ordinary apprentice in the South East and Chatham Railway. At the end of that - this would be in the late 1920s - he in essence was fired from there as most of the apprentices would be, to get another job. The state of the economy being what it was then he couldn't find one for a while and took a job as essentially a labourer with the Post Office, digging holes and putting poles up and so on, and rapidly worked his way up from that.

Coombs

Broadhurst was - there are not very many anecdotes about Broadhurst but I remember one. He married a telephone operator quite early in his life and the two of them had practically no money at all, and I remember him telling me how they got a flat and all they had was a dustbin and a lid, and that was all their furniture. There were a few chairs, a dustbin and a lid, and for the first year of their married life their meals were eaten sitting on two chairs around a dustbin, and when I say a dustbin I mean an English dustbin, that's about three feet high and about two feet in diameter - I don't mean a trash can, I mean a dustbin - with the dustbin lid upside down on the top, and this is what they ate out off. This was Broadhurst in round about 1929 and his wife at that time. He was a very gentle, mild, unassuming man, but he was absolutely brilliant with these relay circuits, and again he served under Flowers and was an expert in the Boolean art although he didn't know it was Boolean. He had never heard the word before, but they were doing Boolean mathematics with relay circuits.

Randell

He was also very keen on design and simplicity.

Coombs

Oh yes, yes indeed. We were all engineers and we all believed in factors of safety. I mean this was a basic thing with an engineer, believing in a factor of safety which some people call the factor of ignorance, and that's what it is in fact. You know the story that an engineer is a man who can make - anybody can make a bridge that can stand up, but it takes an engineer to make it so that it will only just stand up. Well, we were engineers like that. We knew how safe the bridge was. Chandler I didn't know a lot. He was a much younger man than I and he had been working for a man equal ranking with Flowers, a chap called Hadfield who eventually came over to America and joined Bell Labs in Canada and then came to Bell Labs in White Plains. Hadfield was a brilliant man but a difficult man to get on with and I didn't know him very much. Chandler had worked with him. But I didn't really know him until I came in on this work and he came back and we became a team.

<At this point there are a few seconds missing as the tape cassette had to be changed. When the recording begins again it is down at the point where the italics end. See the comments on a similar discrepancy noted on age 28 of the transcript for a possible explanation.>

Randell

From 1936 he'd been involved in the use of thermionic valves for switching.

Coombs

Oh yes, Hadfield and Flowers as well had been involved in what they called 2WF, which is to say the dialling of long-distance calls over trunk (which means long distance) circuits using a voice frequency carrier for the dialled pulses. This was developed by Hadfield and Flowers in the British Post Office. The problem there is of course to make circuits which will respond to dials but which won't respond to voice frequencies afterwards when people talk over the telephone and start flipping off circuits that you don't want to be flipped off. This was their particular line.

Randell

None of these people had had very much involvement with digital calculation.

Coombs

No.

Randell

Flowers had known about the work that Beevers had done on producing a special-purpose machine for some sort of crystallographic calculations. I think at the time they started most of the - they gave mainly - sorry, I will say this again. When I asked questions about did you know so and so, did you know so and so to do with digital calculation then, with respect to the time when they were brought into this work, the answer was normally no. They did not know Babbage; I think Flowers was the only one who had heard of Comrie. They did, however, know about desk calculators; they had seen them, they might have had a bit of experience with them and they knew of the existence of punch card techniques. When I asked Broadhurst about that he said “Well surely it's almost exactly the same as punch tape”.

Coombs

We were, of course, telephone men and the Post Office Telephones looks after teleprinters and telegraph as well, and therefore we were used to the idea of using tapes for transmitting dot dash signals or 5-code teleprinter signals. We were aware of the Boolean nature of things of that sort; this is one of the problems that we had to deal with in telephone working.

?

You said awareness of punch card technology, but were there any people there with very significant experience of punch cards?

Coombs

No, none at all.

?

Was Flowers the Beerage Flowers, you know Flowers, Beer?

Coombs

No, no relation.

?

There were Beerage Flowers who were and still are very interested in Shakespeare and I thought they might very well have been interested in not only in Shakespeare and Stratford on Avon and this sort of thing.

Coombs

Flowers wasn't interested in drama, but he plays a very good bassoon and he can speak Swedish.

?

He wasn't related to the Flowers we had here?

Coombs

I shouldn't think so. He was awfully good at the bassoon.

?

Was there any infusion of television technology?

Coombs

No, none of us were involved in television techniques, none at all. After all this is - there was a British television service in 1936, and we in the Post Office had to deal with transmission of such lines, of signals along cables, but the Research Station at Dollis Hill consisted of two parts that had one man in charge but there was the telephone proper and the radio section and never the twain met. They were rude to each other on all possible occasions - in the nicest way - but they were still rude to each other, the radio and the telephones, and we had no people with us who worked in any frequencies higher than audio frequency.

?

You had no radar pulse people either?

Coombs

No, that is true. Flowers and Broadhurst, and I think Chandler in the first two years of the war, were very intimately concerned with radar techniques. I wasn't with them at this time but I know they were concerned with this, but not with the radar as such. They were concerned with the switching connections from radar station to radar station which were at least as important as the radar phenomenon itself because that was the thing. Radar was known, but how to use it efficiently depended on the interconnecting circuits which Flowers and Broadhurst were intimately concerned with and they went round the country sort of fitting these up and making them work.

Randell

I think it's important to remember that Flowers was in charge of this fifty-man group and, as I put in the paper, they had a great variety of problems, by no means all of them so directly related to telephones as you might expect.

Luebbert

What about the non- linear circuits part of radar. Was there cross- feed there?

Coombs

Not that I know of, none whatever. I think we invented the whole lot that we used. Yes, I'm sure we did. The thing that Flowers did, which I'd never seen done before and which was totally new to me, but is old hat to us now, the thing which he did which I thought was quite incredible was to regard a valve as a thing which was either taking current or not taking current, one or the other and nothing else, so that all the rules about mutual conductances and amplifications and all the rest of it just went by the board. The thing was either down or it wasn't down, and this was so novel to me and yet this was the whole basis of the whole machinery, and of course you know it now. It's Boolean algebra and it's electronic switching using Boolean techniques, but we didn't know it as that then. We just said valves were on or off; they were valves. What you call tubes we call valves and they were better called valves for us because they were things that were on or off, and that's what a valve is.

Randell

Flowers has said that at least some of his knowledge had come from the Wynn- Williams counter circuits and that in particular the book by W.B. Lewis *Electronic Counting Methods with Special Reference to Alpha and Beta Particles* which appeared in 1942 was one that he said came out at just the right moment, that he then - I could probably find the quote, it's in the paper - he then realised with more generality how all of the, a variety of different counting and switching functions could be done with such techniques. Perhaps we should go on to circuit techniques unless . . . . . .

Coombs

I'm a bit stuck here; we haven't got a blackboard or anything have we? We haven't got anywhere I could draw circuits for you; that's a pity. I could enumerate some of the sorts of problems that we had. Part of our technique Wynn- Williams, the man at TRE, the Telecommunications Research Establishment, who was first involved in this sort of thing was an expert on counters. He used gas discharge tubes for his counters, thyratrons and things like that. We didn't like those very much and we wanted to use hard valves. At least Mr. Flowers wanted to use hard valves, and we invented a scale of ten counter which consisted of a scale of two, followed by a scale of five. Every time the scale of two went twice the scale of five flipped once. Now this was a major problem, because while in theory a scale of five counter's an easy sort of thing, in point of fact every time you send a flip into it counts an arbitrary number. You're not quite sure how many it will count; it should just count one but it didn't always and this, I gather - it was before my day - held them up for quite a long time. You understand what I mean by scale of five - five valves with five stable conditions, and the stable condition being used was four valves conducting and one valve non-conducting. The technique is that you feed a pulse into all control grids in parallel; the one that's non-conducting comes down and one of the others goes up. Question, which one? And this was a major problem. Now because of this problem they, thinking about it - the same problem arose in scale of two where you have one valve down and one valve up - you put a plus pulse onto both valves and both anodes come down, then you take the pulse off. Question, do they go back that way, or that way, or that way? And Flowers had quite a lot of problems at that time but he decided - one day he decided that the answer to all these problems lay in one thing - the use of a pentode hard valve as opposed to triode valves which had been used. By that means you could make use of a suppressor grid as an extra switching device so that you connected in the ring of five every one anode through a capacitor circuit to the suppressor grid of the next valve, so that when the valve that was non- conducting came down then when you took the positive pulse off afterwards the one that had been just after it still was negative on its suppressor grid and didn't like it much and stayed down, or rather went up, and the others stayed down so we got a very positive, definite movement round the ring and it never failed. And because of this - this is quite an interesting point - because of our delight at the way in which pentode valves behaved, after the war when we came to use our wartime experience and make the computer MOSAIC, based on NPL designs but our own engineering, we absolutely refused altogether to have anything whatever to do with triodes, double triodes. We said “They're nasty things; we're going to use pentodes”.

?

The Germans built armoured pentodes for their V2 guidance system.

Coombs

Did they?

?

I have no idea of any interrelations - I don't believe there's a digital thing in the lot, because it was a pretty rotten guidance system.

Coombs

I don't know about this at all.

Randell

The pentodes were the EF36s?

Coombs

The pentodes were the EF36s. They had this extra suppressor grid. The great merit of pentode lies partly in the fact that you had this extra grid that you could switch on so that you had a Boolean 'and' function - depending on the phase you were working it was 'or' or 'and' depending on whether it was up or down - but it also meant that when the anode came down it didn't start doing silly things to the control grid because it was screened off by the screen grid, whereas in a triode. you could switch a valve off and in switching off it automatically switched itself on again and that sort of thing which we didn't like. I know there are people who believe in triodes, and all honour to you gentlemen and I'm sure you're absolutely right, but I believe in pentodes. So all of MOSAIC was based on pentodes. As a matter of fact we did hit a bit of a snag there. I agitated for a long time to have pentodes with a rather better suppressor grid - you know you had to switch about fifty volts on the suppressor grid before you could switch the valve off and I agitated to have a suppressor grid with a rather shorter, a rather better mutual conductance to the anode and eventually I got it, and when I got it was utterly useless because I had forgotten that

I'd lost the capacity effect from anode to suppressor so that when in fact you brought the anode down in a switching operation it pushed the suppressor grid in front of it, and that being so it pushed the anode up again and that meant that nothing was stable, nothing worked, which if you had a short suppressor gride base the standard suppressor valve - the standard valve had a very flat part of the suppressor base before it started to go down and therefore it didn't matter what the anode did, the suppressor didn't make any difference to it. However that was a technical point that we found interesting. It's difficult to explain, gentlemen, without a blackboard and chalk. Now I don't know how many of you are engineers and how many are mathematicians, and how many are just interested. Where were we?

Randell

Well questions I guess are just as good as anything -

Coombs

If by any chance you would like to see . . . . .

Randell

Use mine rather than yours.

Coombs

All right, it's the same one, yours is taken off mine. We've got a diagram of a five, a ring of five valves. Now when we started on this, on resistors, in order to get the ring of five valves working we had to have resistors that were pretty accurate in the potentiometers and it was quite a problem to get those because in wartime Britain if you asked for resistors from a manufacturer you got them plus or minus twenty per cent accuracy, and that was absolutely hopeless. Imagine trying to design something with components that are plus or minus twenty per cent. Well we devised a technique whereby a manufacturer still wouldn't give us, say, 22k resistors if we wanted 22k; he'd only give them plus or minus twenty per cent, but at least he was prepared to give us eight varieties of 22k resistors as they happened to come off his production line from twenty per cent high to twenty per cent low at five per cent intervals. He'd give us these separate boxes . . . . .

Randell

Mr. Broadhurst says they wouldn't agree to do that and that you had to do the sorting yourselves.

Coombs

This is - Mr. Broadhurst is out of date. Now what happened was that I started it by doing it myself in the lab and then one of the engineers, Belcher, who was in charge of production, went to the manufacturer and said “What about this?” and the manufacturer said “Yes, we'll do it”. So they did, but I did start it in the lab; Broadhurst is right there. I sat for days on end with one of these moving mirror thingamabobs taking resistors
and putting them like this and putting them in a different box, depending on where the mirror scale came. But the manufacturer did it for us eventually. This is a diagram of a scale of five computer, a scale of five counter based on these ideas - sorry.

?

Did you have to bake the resistors before you used them?

Coombs

No, we didn't do anything. We bought them from the manufacturer. We tried different manufacturers and decided that certain ones were more reliable than others and we tried to get them from them, but we couldn't always. Wartime conditions in Britain were extremely sticky. You see the best resistors in Britain were manufactured in Germany before the war. We couldn't get those any more, and so we had to make our own. And lots of firms set up to make them but they weren't very good.

Randell

Morgan Crucible?

Coombs

Morgan Crucible was one of the best, but this is not a commercial; they were one of the best. Others made them, and others we just never used at all. But they would never do them to better than twenty per cent if they could help it. Ten per cent they would sometimes give you reluctantly and sometimes you had to pay the earth for some two per cents, but even when you got them we found out from bitter experience that they drifted five per cent in the first six months anyway. So we designed our circuits to cope with the resistor that was plus or minus ten per cent and liable to drift five per cent anyway and our circuits could cope with that, and these were the circuits we wired up; these are the circuits we put in and they worked, gentlemen, they worked, and we never had to change them - that was lovely.

Wilkes

What was the pulse rate?

Coombs

The pulse rate on COLOSSUS was five thousand per second, therefore . . . .

?

That seems low, fairly low.

Coombs

Oh yes, oh yes, it was two hundred microseconds for the length of a pulse and the clock pulse was twenty microseconds, one- tenth of that. This was enormously high as far as we were concerned, you appreciate. We were telephone audio- frequency engineers and the anode resistors, for instance, of an EF36 valve that we used - we put, we had a hundred volts on its anode and we put 33k as anode resistor so that three milliamps was its total load; that brought the anode right down. Well with a 33k resistor, quite a small capacitor on the line feeding to the next line, slowed it up quite a lot, and time constants were one of our major problems. That particular problem was solved after the war when we made MOSAIC by inventing a circuit which beat the light barrier; we were all rather pleased with that. That's to say it sent pulses along it instantaneously and therefore quicker than light, but I'll tell you about that later if you like.

Randell

Just one point on pulse speed; you told me that the machine once was run at almost twice the speed, but that it was the paper tape that was the problem rather than the pulse.

Coombs

That's right. We ran the paper tape - oh the electronics could have coped easily. We ran it up to ten thousand, just for fun, one day. The electronics had no problem but the tape didn't like it very much. You can imagine an ordinary teleprinter tape running at a speed of ten thousand characters a second; it's quite fast. What is it anyway? There's ten per inch, it's a thousand inches a second so it's about a hundred feet a second, so it's something more than sixty miles an hour, going round corners like anything, and it doesn't like it.

?

A thousand inches a second, yes that's five times the present magnetic drive.

Coombs

Yes, it's very fast. We ran them up slowly of course. We didn't just switch them on at that rate - - woom, like that; we ran them up slowly, but even so by the time they got up to that speed and they were going round pulleys at this rate, any engineer who knows about belts going round pulleys knows that things begin to fly off when you get to too high a centrifugal force.

Randell

Apparently I.J. Good as a mathematician was quite fascinated by some of the patterns that the tape made and managed to prove analytically that the patterns that were produced did have an appropriate theory behind them.

?

That's reassuring.

Coombs

You mean the paper going from pulley to pulley set up standing waves? Yes. Yes, indeed it did.

?

Dick Lehmer was mentioning today as we were hiking back that his bicycle chains as they were going fast they made a very interesting pattern.

Coombs

Well they'll fly off eventually if you have a belt that loose enough at the time. Eventually it will just come off the pulley by centrifugal force and not have any friction at all. This factor you have to take account of when you're designing pulley drives.

?

On the bi-quinary, I seem to remember that there was a known post- war computer that was designed bi-quinary.

Randell

The 650.

Wilkes

Of course the Bell Relay machines were bi-quinary.

Coombs

ENIAC was bi-quinary wasn't it?

?

Were these independent inventions?

Coombs

Yes.

?

Japanese computer, FACOM 128B used bi-quinary systems.

Randell

Pre- war, Wynn-Williams and/or Lewis had built bi-quinary counters.

Coombs

Mostly Wynn-Williams, I think, used gas tubes.

Randell

But of course, as somebody pointed out, the notion of biquinary goes back at least to - I can't remember whether it was the Chinese or the Japanese abacus.

Coombs

We've got two hands with five fingers each, haven't we? that's bi-quinary - crikey!

?

The Romans used bi-quinary long before the Chinese.

Brooks

There are two different kinds of codes called by that name. Some of them had two out of five codes, which were very common in telephone circuitry; some of them in fact were seven bit codes.

Randell

That's how I was using bi-quinary, and that's what I meant by abacus too. Where were we? John, you were . . . . .

?

What was the speed of the tape, when you normally run it?

Coombs

Five thousand characters a second, and there are ten characters to the inch, so that's a thousand characters a second, a thousand inches a second, which is a hundred feet –oh no.

?

No, this is not a thousand bits; it's a thousand characters, so it's quite a lot faster than this.

Coombs

Well, one character is five holes across a tape.

Randell

Have you any idea what speed the electronics might have gone at?

Coombs

Well, we tried them up - the electronics would probably have stopped quite soon - look, here is a two hundred microsecond pulse, which is a character pulse. We had a technique whereby the characters instead of just being short pulses were lengthened out to be the full length of the counting pitch - the pitch of pulses, they were lengthened - an upward pulse lasted and if there was another upward pulse it stayed up - otherwise it came down - so it was a hundred per cent efficient in that sense by the time we'd switched it. Now, that pulse was two hundred microseconds long. When we switched that pulse from one circuit to another one we switched it on; we passed it through into the new read-off circuit, and then the counting pulse that read it was a twenty microsecond pulse at the end of that two hundred microsecond pulse. So from switching stage to switching stage we had two hundred microseconds available. That was going at five thousand a second. Now the circuits, the 33k anode resistor with such capacitance as existed on the leads going to the next circuit, were such that the build- up of voltage was adequate in that two hundred microseconds. If we halved it would probably still have been adequate, but if we'd come down much quicker it would probably not have been good enough and in that case we'd have had to diminish the anode resistors and would have had to take more current and put in more beef and all the rest of it. The solutions were there - we'd have had to use higher screen voltages, longer grid bases and all sorts of things like that. We could probably have doubled our speed; we might even have trebled or even quadrupled our switching speed as far as the electronics was concerned, but we were limited by the speed of the tape, which could go comfortably at five thousand characters, that is to say, one thousand inches per second; that's what it would do.

Randell

And the main reason they could get the tape at five thousand rather than anywhere from a thousand to two thousand that the Robinson used was because there was no longer any question of a sprocket wheel . . . . .

Coombs

That's right.

Randell

. . . . . there being just a single tape driven by friction, the sprocket holes being used as the source of the clock pulses.

?

If I understand you correctly, you described non- recurrent zero in coding.

Coombs

Yes, that's right.

?

. . . . which became popular in tape drives, magnetic tapes very considerably later. Again an independent development?

Coombs

Yes, we just wanted the pulses to be as long as possible so we arranged that they were; we didn't know we'd invented anything.

Randell

I think this sort of thing, the circuit techniques, were certainly used quite openly afterwards and published quite openly. They were used in MOSAIC for example, and I refer to a 1954 paper which describes the electronics of MOSAIC.

Coombs

This is my paper, yes.

Huskey

Did you sense the holes in the paper?

Randell

Well, that it was done photo- electrically with the double-crescent mask. This is about the one picture that you can probably see from there. This was a mask - that's roughly actual size, probably slightly increased in size and that - imagine the tape going this way and you're reading the five holes twice, so you were reading one row there and one row there, and the double-crescent was devised as something that gave a pretty square pulse of light as a hole passed it, and there was a lens system - it was once drawn for me - a quite complicated set of lenses to deal with a mask that big and a paper tape about that wide, and that was the stuff - the machine - the reader - that was developed in the physics group at Dollis Hill under the name the Mark I telegraph transmitter by people who had no idea that it was anything to do with the COLOSSUS or Bletchley Park. But originally they couldn't - because of the way electronics on the Robinsons - that would work at only about two thousand characters a second - I'm sorry, I've mixed two things up. There were two reasons, the way the electronics were done and the sprocket hole problems.

?

What about those characters, what happened to them? Was there a buffer store of any kind or was all this done on the fly?

Randell

I can say a little bit about that - no, I was thinking of the Mark 2. The Mark 2 machines, all the production machines, effectively worked at twenty- five thousand characters per second and their shift registers were used to allow a five-fold parallel working.

?

Reading five tapes simultaneously?

Randell

No, reading one tape at five thousand characters per second, but then processing, using shift registers so as to process five characters, but we'd better watch that.

Coombs

Well, one character five times and different problems.

Randell

Yes.

Coombs

It was parallel output, yes that's right; it was parallel but it saved a lot of circuits. The limitation on speed would probably have come from the photo-electric readers which were pure amplifiers. These were the only parts of the machine that were amplifiers and not on/off devices. They had to read the photo-electric signal, amplify it, sharpen it up and all that sort of thing, put frequency correction in, and they were quite tricky; they wouldn't have gone much faster.

?

How about the shift register? How much store did you have?

Coombs

Well the shift register in effect - take any one signal coming from any one photo- hole in a tape from the mask; you've got a signal like that. Now you put that into a memory circuit which squares it up. That now is stored in the memory circuit. It's going to be passed on from that memory circuit to four other memory circuits so it now occurs five times in a row. It's there, five times in a row. You do what you like with that signal, five different things.

?

So you had in effect a five- character store?

Coombs

A five- character store, but of course in the meanwhile the second, third, fourth, fifth characters have come so you've got five characters in a shift register, the current character and characters up to five back. You do tests with those, and then they just fall off the end.

Randell

There were other things on the machine like thyratron rings for holding information as well.

Coombs

Yes. I think Brian Randell makes very much the point here, and very succinctly, when he says that the major advantage, or one of the major advantages of COLOSSUS as opposed to the Robinsons was that Flowers stored some of the information in the machine instead of having it on another tape, so we had one tape and it was generated in the machine, the other tape was, and that was . . . . .

Randell

And that other information was generated dynamically based on, shall I call them, parameters, which were set up by means of switches and plugboards . . . . .

Coombs

Right.

Randell

. . . . . onto thyratron rings and an important effect of this - an unanticipated effect, at least unanticipated by the mathematicians - was that it became possible now to let the processing depend dynamically on what had been achieved to date, where previously one was talking about two read- only inputs, shall I say, the paper tapes. Let me go back just to the reader for a moment. The only - dare I use the word 'prior art' as a patent term - the only thing that I can determine that Lynch and Speight, the people who did the reader, had as a relevant background was that one of them - I believe Speight - had been involved in the design of the Post Office's speaking clock and that that had involved photo-electric - taking information by means of photoelectric cells and lenses and the like.

Luebbert

I'd like to investigate this area of control a little bit because telephone signaling people have a wide variety of different kinds of control techniques and I'd like to, if we could, try to get an idea of the relationship of ideas that came out of telephone signaling and the various kinds of control that we've been talking about in the conference like plugboard control, etc. etc. Could you ….

Randell

The plugboard and the switches on COLOSSUS were based very directly on the auxiliary machine that Morrell had built for the Heath Robinson. Those, I believe, were based rather directly on the needs for the process that the Heath Robinson was automating, and I in fact don't know - even if I did I'm sure I could not go further than that. Doc?

Coombs

There were various racks on the COLOSSUS machine. Most of them were thermionic and there were about two thousand four hundred valves, but nevertheless - that's the production machines - nevertheless there was one rack which was called the 'S' rack which stood for switching, on which all the overall comparatively slow control processes were performed by Post Office electromagnetic relays, setting up quite slowly as between one test and the next or something like that, set up in slow time with ample time to do it set up in this way. That rack also contained rotary line switches, you probably call them - uniselectors we call them - I don't know - a rotary switch which can go round twenty- five outlets and then another twenty- five outlets sort of thing. We had lots of these on the rack and they were the worst part of the equipment. If you got any trouble it was the rotary line switches, but we as telephone engineers knew that, because we always expected the trouble to come there. We were wrong to put them in but we thought we could get away with it and we didn't. This was where most of the trouble came; the relays gave no trouble, the valves gave no trouble. Sometimes the paper gave trouble, sometimes the input/output things like teleprint - like automatic typewriters and things like that. But there was a master switching rack with electromagnetic relays and these were designed - this was the rack that Broadhurst designed when the circuits were torn up and given each of us to design - Broadhurst had all the 'S' rack stuff because he was an expert on those things. There was another rack called a 'K' rack which had lever keys, or perhaps I should say lever keys in this company, telephone switches which you switch on and off and a whole rack of those so that manual functions could be set up. There were other rows of plugs and jacks which could be set up. There was an 'M' rack - I think that was a master control rack which had valves on it mostly. There was an 'R' rack which I designed most of, which was the remembering rack which did this five back technique and things associated with it, and so on. There were racks having different functions like that, nearly all thermionic but at least one rack all relays and uni-selectors and deriving from Post Office practice and technique.

?

As regards this tape, how did you splice this tape?

Coombs

We tried a lot of experiments in joining tape, and eventually we came out with a most interesting device called a parrot stand. It stood about this high, like one of those free- standing ashtrays, and then it had two pieces of steel standing out like that, and you put the tapes to be joined across - you used holes at the end and put them like that in the middle - and then you used to join them the only stuff we had found to be effective which was the stuff called Bostik. And we painted these surfaces; we put them together and put something else on top, heated them with a local heater, opened them up and there they were. It was absolutely vital that the join in the tape should be dead square and not in any way not straight, hence the reason why you have the long ends to keep the line square. And we joined them with Bostik and this was effective. I don't know if you have Bostik over here; it's one of these commercial sticky things - well we had it.

?

Yes, we have the same stuff we used for . . . . .

Coombs

Yes.

?

When are you going to tell us about Turing?

Coombs

Well we had a lot of stories about Turing. The thing about people like Turing is that he's such a brilliant man; he stands out so much above everybody else that you can only tell stories against him. These are the only things that are interesting; they somehow make him seem human instead of what he was, and anyway I expect there's possibly a little bit of jealousy in it and you can say “Oh of course he does do silly things sometimes” so in fact anybody who tells stories about Turing tells them against him. This is not right; this is no trouble, it's really a great compliment to him. So I can tell you just one or two things which are quite funny, if I can remember what they were. I must say by the way that I didn't meet Turing until after all this. I met Turing in about 1946 or '7 when we were going to build the ACE Pilot model, the ACE for the NPL. Well that's when I first met him. Although he had been designer – on the early concept of the methods to be used in the Heath Robinson, and of course the same methods prior to COLOSSUS, he'd gone off that work by the time I came on to it, so I only met him after the war.

Randell

Turing had a close involvement with Broadhurst and Flowers?

Coombs

Yes, but not with me. So about Turing, let me see now, there were about three things I remember that I always like very much. You know, of course, that he was a cross- country runner, do you? He was very fond of cross-country running and when we had meetings up at Dollis Hill, which is in the north- west of London, the Post Office Research Station - it's about fifteen miles away from Teddington which is the NPL which is where Turing worked. So what used to happen was that Wilkinson and other people from NPL used to come up to Dollis Hill by train bringing Turing's clothes, and he would run, he would run, he'd put on his shorts and he would run these fifteen miles up to Dollis Hill. He would arrive roughly the same time as they would - I think because he started earlier, not because of London Transport - and then he would take his clothes and go into one of the toilets and change and then he would come in and all the rest of the day he would drink vast quantities of water. He would just knock water back all the time and he would always stay on his feet; somehow he was restless to get going again, and this is the sort of thing that happened when we had meetings at Dollis Hill. I remember there was a particular thing about . . . . .

Huskey

I have a point about that . . .

Coombs

Yes? Oh, you were at the meetings too, of course you were.

Huskey

I made such a race - I beat him by about ten minutes. One of the reasons that it's more competitive than it sounds is to make the train schedule - you have to change trains fast and that makes it a little more difficult.

Coombs

And especially when you bear in mind that one of those trains was Southern Railways. I think that answers the whole question myself; I'm not an admirer of the Southern Railway. Someone mentioned about Turing describing - what was this thing about 'consider a set of dots' or something. Somebody mentioned this at a meeting the other day. Being a mathematician he had this incredibly obscure way of describing something that was painfully obvious, really. Well he was - I remember when we were having - well when we were doing the ACE, when we were looking into the ACE and the other machine that we were making we had meetings at the Adelphi Hotel in London, and this was at a dreadful time when we had no coal, no coke, no fuel. We had ice all over the place for three months and we had these meetings from ten to twelve in the morning and from two to four in the afternoon, no electric heating - the lectures were by oil lamp - and Turing was a lecturer and Wilkinson was also a lecturer. But I remember Turing explaining to this assembled throng, which all knew very well what it was, what a trigger network was. And he had a blackboard at the back here, and instead of just saying “Well a trigger is a two- state device with two stable conditions” he said “Consider - blackboard - a region and a region” - all as mathematicians do - and then he drew an arrow up here and said “Here's the trigger; now it goes there or it goes there.” And it became a standard joke for us a long time, whenever we had to consider by stages of anything like that, whenever we started an explanation to any one of us, when anybody explained any circuit to anybody else we always started by saying “Consider a region” because it showed his technique. But he did commit one lovely crime, I thought. We mentioned the other day, also, somebody who added, one of these idiot - what do you call it, idiot savants - who counted using the highest number first and going backwards down to the lowest number. Well I remember Turing at Cambridge, at the conference that we had there in 1949 at the time that EDSAC was opened, I remember Turing putting up on the board, advocating, writing numbers in the opposite direction, and he wrote up on the board a number, 1234, and that was not one thousand two hundred and thirty- four but four thousand three hundred and twenty-one, you see, but he wrote it 1234. He said “This is much the best way to write numbers with the least significant digit first”. Then he wrote another number underneath it like 5678, you see, least significant digit first and he said “These are very easy”. And then he added them together and he started with the most significant digit over on the right and carried it to the least significant. That was really quite reassuring to find Turing doing a thing like that. But really, that's about all.

Randell

Despite that, Broadhurst who was - I don't think it's at all impolite to say - far from being a mathematician, classified Turing as a born teacher and it’s very clear that during the war in the period '42 to '43 and so on, the mathematicians, particularly Newman and Turing, and the engineers were, after perhaps an initial period of mutual incomprehension, working together very closely indeed.

Coombs

Yes, we did work closely, yes, fine, but I didn't know Turing at that time.

?

You couldn't have had COLOSSUS without Turing, or could you?

Coombs

COLOSSUS was an engineering interpretation of a mathematical problem. His was the mathematical problem which was solved by Heath Robinson, not very well.

Randell

I don't, in fact, think that's quite right. According to Professor Newman the problem goes back rather more to Professor W.T. Tutte.

Coombs

I don't know that.

Randell

Turing had been involved in extending the problem. Turing was not directly involved in the meetings on COLOSSUS. It's believed that he was very much involved in the early days of Heath Robinson, and he was even more involved, or at least as much involved, in the set of rather different machines for different problems that Flowers and Broadhurst, shall I say, cut their teeth on. It is really rather difficult to determine Turing's direct responsibility for COLOSSUS. I think directly it was very little.

Coombs

Well, the fact is that I came in at the beginning of the COLOSSUS era and I never knew Turing till 1946. I never met him, didn't know about, never heard of him.

Randell

Well you came in when the prototype was almost complete.

Coombs

Yes, that's right. I'm not disputing his effect on the problem, but he wasn't concerned with the machine.

?

What we were trying to determine is, did he contribute intellectual chains of thought that were unknown and which couldn't have been - would the aim of the machines have been successful if they hadn't had him?

Coombs

I can't tell you, because that was done before my day.

Randell

There were a number of different problems worked on, in series and in parallel, and Turing and others made a number of contributions to a lot of them. All the work was divided up into compartments; I have the impression that Turing moved between compartments more than others.

Coombs

I think this is true.

?

Because his work with denumerable quantity(?) . . . . . involved that kind of thing.

Evans

Can you say who actually insisted or pressed for this being a valve machine?

Coombs

Do you mean COLOSSUS?

Evans

Yes.

Coombs

That – of course Heath Robinson was also a valve machine.

Evans

Let's go back. Who was it who said "The only way to do this problem is by using valves"?

Coombs

Flowers.

Randell

If you go back to Heath Robinson, Flowers was not involved at the beginning of Heath Robinson. That seems to be between Newman and Wynn- Williams, though the suggestion there is that - I may be getting confused - but I think Turing might have been involved in the suggestion there.

Evans

This is what I was wondering, whether some of the brainwaves were Turing's.

Coombs

I think that Heath Robinson was based on Wynn-Williams' experience with gas tubes; he was a counter expert, and such things as that. I was first brought into the project when the first Heath Robinson came along - when the second Heath Robinson came along - to make it work.

Randell

What about manufacturing problems?

Coombs

Oh no, to make it work, to function the thing; that was the first job I had with that group when I first came in; I had to function it. I didn't like it much. I was new to this art anyway and I couldn't think of any other way because I knew nothing about it but I didn't like very much what was happening, and Flowers by this time didn't like it very much. It was a sound enough machine but we didn't think it was a soundly engineered machine. It didn't really seem to fulfil engineering properties. This is not in any way belittling Wynn-Williams, please, I'm not doing that. It was his engineering concept to begin with. So when Flowers saw what the thing was all about, and this only happened by degrees because first of all we were brought in as assistants without being told anything and we slowly learned more and more, and once it was learnt Flowers said "No, I don't think you should do it this way. I think you should, for instance, generate a lot of information internally and not use pairs of tapes and things like that, and you shouldn't use sprocket holes and you shouldn't use soft valves and you shouldn't try to use the output of a trigger to drive something else because that'll stop the trigger working. You must put a buffer valve in and you must have output valves and you must do this and you must do that." And the objection to that was from Wynn-Williams again on the TRE side - he was naturally asked “What do you think of this?” and he said “No, it's no good; it won't work because valves are unreliable things. They tend to blow their heaters and you'll always have half a dozen valves not working. It's no good putting a lot of valves in like that.” And this argument swayed the day because, after all, he was the professional adviser and the Foreign Office said “No, we don't want this thing done like that.” But, that was when Flowers went to our chief, Radley, and said “I think it ought to be done that way, anyhow”. And Radley said “Okay, you do it, and I don't know where the money'll come from, but you do it”. And we built a machine to do what we thought was right, and just at the crucial moment when the other machines weren't solving the problems Flowers said “Well look - actually we have got a machine and if you'd like to try it . . . . .” And so they came along and saw it and it was installed and, as the report says here, they were absolutely staggered that this machine that looked as though it was made with string and toothpicks, because that was all we could afford, not very good quality toothpicks either, well that machine solved its first problem in ten minutes, which was quite incredible, and then they did the same problem again and got the same answer, and it was the right answer, and they said right away “Oh yes, please, we'll have some of those”. So Flowers was the man who turned the Heath Robinson, which was a good idea but not good enough, into COLOSSUS which was brilliant, and in all honour to Wynn- Williams he came along and said “You were right, you know; this is absolutely the way to do it. Congratulations”.

Randell

On valves, let me just go back to Turing for a moment. There's one anecdote that Turing on return from one of his wartime trips to the States, his sole reading was a book on valve characteristics. Apparently his character was such that he would not be able to forbear from tinkering himself with the electronics. I think one of you said “The less said about him as an engineer the better”. Towards the end of the war he seems to have done some work on scrambling telephone messages and there was a period between his leaving Bletchley and his arriving at NPL which is unaccounted for, apart from the fact that it seems to have been a time when he was actually building electronics. It's rather unlikely that those electronics worked, I would have guessed.

Coombs

Well as an example, in these lectures at the Adelphi, when he told us not only about the theory of the ACE which we were to build but insisted also on telling us how to do it by showing the engineering, I remember that his idea again he had the idea of economising equipment which is no good in this sort of stuff - his idea was that you had the mercury delay line and you come round through a device called a super regenerative amplifier which gives a gain of about ten million to one or something like that, and feedback that into the delay lines so you can do all your gain with one valve, and this he thought was very, very good. And we listened to this absolutely horrified because we knew all about squegging and white noise and nasty things like that, and it seemed that what Turing was doing was building in deliberate instability into a circulating circuit which would have to circulate with absolute safety. If this was going to hold numbers then it must not lose a pulse or gain a pulse anywhere, anytime, under any conditions, and he was building in instability. So we said “Yes, yes, I see, yes, oh yes, I see” and went away and did something else. Of course you couldn't argue with Turing, but it wasn't a good idea, but he'd read about it somewhere and just wanted to incorporate it because he was that sort of bloke. Anybody ever use a super regenerative amplifier for something that's never got to go wrong?

Huskey

When I arrived at NPL in January 1947 I'd just continued some experiments with a crystal delay line using a twenty- foot piece of certified (inaudible) as a delay line, and he burnt this out, so the experiment was finished.

Randell

His 1945 report on ACE - proposal for ACE - just has one brief comment on the fact that he had experience with, or perhaps it's experience of, electronics, but that's the only mention.

Coombs

He wasn't really an engineer, but he was a very, very brilliant man.

?

I must say, from the stories you've told me about him, it seems quite contradictory. You gave the impression that he was an effeminate person; I cannot imagine a mile runner being effeminate.

Coombs

He wasn't effeminate. He had a rather high- pitched neighing laugh, but he wasn't effeminate, no. I think perhaps we shouldn't pursue this topic; it's not really a very good topic to pursue, with Turing.

Randell

As regards reliability, as far as it can now be remembered, the COLOSSI had perhaps about one fault per week on them. Let me say that they were used intensively but not go further than that, and that they were used intensively till the end of the war.

?

Which end?

Coombs

They were used after the end of the war.

Randell

One or two of the members of the team said there were more problems with the valve holders than the valves.

Coombs

Because these are dry contacts.

Randell

And you gave the story of one of the problems with the paper tape, not the paper tape reading, but the paper tape itself cutting through the steel guide pins that were meant to hold it in position because of the speed at which it was going.

Coombs

Hardened steel pins, and they would slice them through like mad after a few days or weeks running.

?

Were the machines off and on, or did you leave them on all the time?

Coombs

The thermionics were on all the time, and so much so that at Bletchley we had a special cable run from the power station into there to provide a permanent supply of power, and in any case whereas some places had blackouts, Bletchley never did. The inhabitants in Bletchley were very lucky; they didn't get their power switched off at all, only because of our machines. We had a special cable run as a reserve thing, so we never, never, never switched anything off; once if was on, that was it.

Randell

That was part of Flowers' decision to go for a large number of valves right from the beginning.

Coombs

Yes.

?

How did you know you had an error? How did you know if you didn't have an error?

Coombs

It's the sort of problem that doesn't arise. You know, really if you're driving - oh dear me, see if I can think of an analogy that doesn't give anything away. You're looking for an answer, you get an answer, you then try that answer out on the problem, it doesn't work, therefore you have had an error.

?

All right, a very perfect, a very easy example of that is to find the factors of something.

Coombs

Yes, multiply them together. Yes, but if you get some wrong answers, well you might have missed answers but I don't know that they ever did. The things were coming out in the expected manner; answers were coming out in the expected manner and the answers were proving all right.

?

Well what does it mean to have one error a week?

Randell

That about once a week it was necessary to provide - well, the IBM term would be unscheduled maintenance I think.

Coombs

Or repeat a test, that's all. They were not cumulative; it was - virtually the whole system was virtually self- checking because of the nature of the system as it was.

Randell

Oh, incidentally, in my paper I mention that the total number of valves used in the entire installation for the various machines there has recently been estimated as somewhere between twenty and thirty thousand.

Coombs

By the way, there's one thing; you suggest in your paper that the name COLOSSUS was given by the users. In my recollection this was not so. In fact, the story I have to tell you again redounds to the excellence of Flowers' ideas. He designed this machine and he was impressed himself by the size of the number of valves in it and he called it 'a colossus' you see, but by the time that machine had been in and we'd got some orders I remember him saying to me “You know we were wrong calling this COLOSSUS”. He already had envisaged much bigger machines using even more valves. He said “We're quite wrong, we've used the biggest name we can. We should have called this one 'Baby'“.

Evans

Since you mentioned the original Turing report, I thought people might like to know that because this was a proposal that Turing wrote in 1945 for ACE, I believe, we've had that republished with the original, with replication of the original notation and drawings, at NPL. It makes very interesting reading.

Randell

Let me read out what I've put in my bibliography about that. To be exact, what I've put here is about the paper by Carpenter and Bob Doran sitting next to you there, which is an analysis of Turing's 1945 report and the draft report on EDVAC under von Neumann's name. I say that Carpenter and Doran's paper provides an excellent analysis in modern terms of the original design for ACE given by Turing in his 1945 report and a comparison with a slightly earlier EDVAC report by von Neumann. It points out that in contrast to the von Neumann report, which is incomplete, with neither the I/O mechanisms nor the details of the central control being spelled out. “Turing's paper, on the other hand, is a complete description of the computer right down to the logical circuit diagrams with an exhaustive thirteen-page analysis of the physical properties of the memories and a cost estimate of £11,200. Amongst the topics listed as discussed in Turing's report, but not found in that by von Neumann, are address mapping, instruction address register and instruction register, microcode, hierarchical architecture, floating point arithmetic, hardware boot- strap loader, subroutine stack, modular programming, subroutine library, link editor, symbolic addresses and the ability to treat programs as data”.

Evans

If I can add to that, if anyone would like a copy of this, if they let me have their names and addresses I will get it sent to them directly I get back to England.

Randell

That was, I think, what was known as the Model 5 ACE and there were a lot of iterations as we have already explained to us by Jim Wilkinson.

?

It was the Model 1.

Randell

Oh, I thought it was Model 5.

?

I occasionally talked to von Neumann about that period and I think he thought of the technology as being very fluid and that possibly was one of the reasons he wouldn't have spelled it out.

?

Are you able to tell us anything about the nature of the problem, how many permutations?

Randell

No. The next topic I've got here, if you'd like to move on to that, is the design, building and commissioning of the Mark 2. Well we covered most of the design side. I think I've already told the story of the commissioning, how the Mark 2, the two thousand four hundred valve machine was ordered in March and the first one was working by D-day, but I didn't say very much, at least yesterday, about the building and the handing on to the technicians in Birmingham and so on.

Coombs

Well, what is there to say? We had the job to do. I sat down to this work. I'd never been in charge of a production programme before. I was in sole charge by this time of the making of these things. I'd never been in charge of anything like this, but fortunately I had done engineering production as a young student at college. I took my staff and I took out the best men and I put one man in charge of three or four other people and said “Right, you do such and such a rack; here's your equipment”. We brought in staff from all over the country . . . . .

?

You said Birmingham.

Coombs

Birmingham helped us on the later ones when we found we just couldn't keep up. We employed as many staff as we could, as we could get, but a lot of - the Post Office, of course, had to keep its telecommunications working and anybody spare was already in the forces. We got people everywhere. We vetted them. They weren't told mostly what they were doing.

?

To be clear about the date, this is after the June deadline?

Coombs

This is from about February 1941 - sorry February 1944 - when we knew what was going to happen. We got people, and Flowers was instrumental mostly in shaking up staff until - we got people in, we got them away. People were very reluctant, but we got them. We put them in charge of little gangs. We took over half the research station. I had splendid Skilled Workmen, Class l, as we called them - you know, the sort of workman who's done it for forty years, all his life, he's totally reliable, knows what he's doing, totally prepared to work and give all the time necessary. Two of them were ex- navy - they were that sort of people. They were in charge of the gangs. I kept records of the gangs. I had production charts on the board. I gave pep talks every so often. I solved all their little problems of all kinds, marital and otherwise; I was father confessor. I gave lectures. I had to keep my eyes open to pick out the very best of these chaps, and they were selected and asked if they would like to go out on special work. They were vetted and if they were all right they were told about the whole project and then sent out to Bletchley as maintenance men. But in the meanwhile production went forward. Half the research station was a production factory for work which none of the people working on knew what it was for and they were working seventy- two hours a week on it.

?

So in the COLOSSUS there were twenty or thirty thousand valves.

Randell

No, I said that the total number of valves in the installation covering all of the machines there was between twenty and thirty thousand valves. The number in even the first Mark 2 COLOSSUS was two thousand four hundred, and it may have gone up slightly because no two COLOSSI were exactly the same.

Coombs

We were adding facilities all the time.

Randell

And sometimes facilities were back- added retrospectively - retrofitted, that's the IBM term!

?

Did you build the COLOSSUS at Dollis Hill and then move it?

Coombs

No, at the beginning, I think, although my memory - you know it's a long time ago - I think we assembled each rack and tested each rack as far as we could for the first one, because this first one we had to do in something like three months, and I had charts showing how we were getting on, which rack was behind and which gang was letting the rest of the side down, and all the rest of it. I think we tested the racks at that time, but then we shipped them out to Bletchley and fastened them together, and the soldering together, and joining them together was a major problem. Later on, Flowers I think it was again, went over to Birmingham and saw the Post Office factory there and had a long talk with them and a lot of the work was transferred to them using their skilled wiremen, and some of our junior engineers went out and acted as clerks of works on the job and they were sent from Birmingham straight to Bletchley so they didn't come to Dollis Hill. The technique for mass production using these resistors that I talked about earlier on in five per cent groups - the drawings were made in such a way - it's mentioned in your report so I can say it - in this drawing, which is a drawing of a counter, this scale of two counter, there is a note saying 'resistors on this rack should belong to groups D, or E, or should belong to all one group, so that we could use resistors which were, say, 220k resistors, 56k resistors, 33k resistors, but they had to belong to the ten to fifteen per cent, or any one group of five per cent group had to go on that rack so that they didn't have to test every resistor before they put it in to see if it was right. They got a box that was group D and those they could use on the whole rack, and as far as I could I tried to make any one machine belong to one resistor group. If I couldn't do that I made any one rack belong to any one resistor group, and if I couldn't do that I made any one panel belong to any one resistor group, and this enabled production to go ahead fast. We had to work out all these things as they came along, and we were one hundred per cent devoted. We didn't do anything else; we did this and this was our work. We didn't want to do anything else, except that every Thursday I went and courted my fiancée, but apart from that that was all we did. And we got the thing going. It was a production line organised on the spur of the moment, but by people who were wholly devoted to getting that production line going, and we got it going.

Randell

The next thing I've got listed down here is probably the most difficult of all of the topics, and that's the assessment of COLOSSUS as a program-controlled computer. I covered that to a fair extent in my talk; I was working directly from what I have written here. It seems that there was probably rather a difference between the prototype, the one that worked in December 1943, and the production ones, the first of which worked in June 1944, but that from June 1st 1944 the

COLOSSI had this logic switching panel which apparently allowed what certainly I.J. Good describes as the programming of serial and parallel Boolean operations and it was that that was used by <*Geoffrey Timms, for example, to demonstrate that multiplication could be done by the machine, and there was some form of conditional branching as well.*>

> <*There was a problem with the recording at this point because the tape cassette had to be changed and a few seconds of the session were not recorded. The last sentence from "by Geoffery Timms, …., was not actually recorded. So where did this come from? A search of Brian Randell's archives revealed a May 19, 1977 letter from Nick Metropolis, the organizer of the Los Alamos Conference, thanking Brian for a copy of the transcript of my recording (likely sent to him by Betty Smith, Randell's secretary who had made the transcript) in which he indicated that: "I have explored the situation here and we do indeed have our own recording. I am having a copy made that we can send you."*
> *Betty Smith must have used that to fill in the missing gaps in the transcript of the original recording.*
>
> *This missing material includes everything here noted in italics, the question below asked by Don Knuth and, perhaps, some part of the answer given to it. The fact that Randell appears to be partially through an answer suggests that the original transcriber managed to fill in some of the missing discussion but, perhaps, not all of it.*
>
> *The Los Alamos recorded version of this informal session appears to have been lost. The fact of this second recording being made is hinted at on page 34 of this transcript..*>

<*Knuth:*

I was going to ask if you knew of anyone who had actually played around with it for programming non- standard applications>

> <*The recording continues from this point*>

Randell

The other thing is that it was only used - the multiplication I'm sure was just a side issue. The actual use of the machines was all for the work that the Newmanry and the Testery were involved with. However, within that area they were used for quite a variety of tasks. Without making any change to the machines, they were used for tasks which had not been thought of when the machines were first designed.

?

My other question is about this product aspect. Did the people like Flowers know in much detail the programs that were going to be run?

Coombs

Yes we did. We were by this time quite in the confidence of the people. We knew as much as we - anything that we didn't know we could ask and be told, but we didn't know everything, not because we weren't told but because it wasn't necessary. We didn't have to; we knew the problems.

Randell

I think also that during this time there was a lot of development of techniques, and in particular one of the things that was done on the machine was a task that was previously associated only with the Testery and thought of as being essentially a manual task and it was later on, I think in late 1944 or early 1945, that Shaun Wylie showed that this apparently solidly manual task could be automated completely without any change to COLOSSUS.

Coombs

That is actually quite a point there. I think it's worth saying that one of the developments that Flowers put in on COLOSSUS as opposed to Heath Robinson was that he did put in the facility for doing Testery work which Heath Robinson hadn't got. He put it in off his own bat.

Luebbert

There seems to be a strange similarity in the way that you describe the control panel - a sort of Boolean equivalent of the control panel on, say, an IBM 600 calculator in the sense of plugboard type of programming but for Boolean rather than arithmetic operations. Could you comment on that?

Randell

Well these were separate things, the plugboards and the logic switching panels. The plugboards were the ones that came from the auxiliary machine and were to do with the setting up of the parameters for the data that was to be generated internally. The logic switching panel was, I think, just banks of switches.

Coombs

And also plugs and jacks, and cards and things.

Randell

I think it's quite possible, indeed probable, that knowledge of plugboards on IBM and Hollerith equipment could have been an input to this work. Certainly the people say certainly we knew about IBM equipment, except that they called it Hollerith equipment.

Coombs

I can amplify this, I think, quite reasonably. The Heath Robinson was made to function by virtue of rows of jacks and cords which you plugged up to get the appropriate function. When we came to COLOSSUS we looked at this and said “Well that makes a horrible sort of rat's nest of things hanging off. That looks like a big telephone exchange with all sorts of criss-cross wires. Let's make it a cordless board; let's make it a panel of keys”. And we just turned lever keys instead of hanging wires all over the place, and we did it like that. But we also provided some auxiliary functions with plugs and jacks. This was all it was. It wasn't knowledge of plugboards like that or anything. It was just simplifying something and a tidying up operation from the point of view of the operator.

Leubbert

So it was analagous to a communications control board?

Coombs

Indeed it was, yes, that's right - in that sense.

?

I would like to ask a question that has really nothing to do with the past but with the future. All these super machines seem to be designated for numerical work or something that the computer scientists consider to be terribly remote from mathematics. I have curiosity as to things that are Boolean and combinatorial in nature. What about special- purpose machines? Do you think on the basis of your experience there would be a real extra order of magnitude of power for Boolean and combinatorial- type constructions that could be achieved for a machine dedicated to this purpose?

Randell

Oh I think certainly people sometimes find that by going down to an even messy level of microprogramming they sometimes find that those sort of problems could be done very - with a greatly increased level of efficiency. To describe the COLOSSUS entirely as a Boolean calculation machine is, in fact, incorrect.

?

I wasn't thinking about that.

Randell

I realise that, but I thought for the record - it certainly had counters built into it and, let me say rather carefully that it had arithmetic tasks as well as Boolean tasks.

?

What was the output?

Randell

It was an automatic typewriter.

?

Several?

Coombs

Just one.

Randell

It shows up in the photographs. I think that there were also lights and things on it as well. There was a fair amount of interaction with the machine, or at least there could be.

Evans

How was this fast enough, a single typewriter, feeding out results or whatever happened?

Randell

Perhaps there weren't many results.

Coombs

There weren't very many, no; that's the point, that is the whole point. It's just you're looking for an answer and it eventually comes. It has got - I don't know whether you made the point earlier on - it did have the facility, discovered by accident, for man/machine interaction so that you could talk to the machine and alter its characteristics and it would change and it would change tapes and you could play it like a toy and change it. You couldn't do that with Heath Robinson or any of the others; with COLOSSUS you could.

?

You had five thousand characters a second and ten characters a second out.

Coombs

Well yes, it didn't even have to be as fast as that.

Randell

Switching from that, arbitrarily, something I didn't cover at all in my talk is the, shall I say, the extracurricular activities by Alan Turing with a group of the younger mathematicians there, particularly I.J. Good and Donald Michie and some others, on thinking about, well I guess what we would now call AI. I think probably the best thing is if I read the chunk that I've got here. “The Turing machine did provide the conceptual background for Turing's extracurricular work on and discussions of the idea of thinking machines. In the main these discussions were with some of the younger scientists at Bletchley Park. The more senior ones tended to disapprove of such science fiction-like topics. He concentrated on game playing as an arena in which to test out his ideas, and on chess in particular. It was through a common interest in chess that Michie got to know Turing and to become involved in the idea of machine chess. Because of the methods of recruitment at Bletchley Park those of Turing's circle there who played chess at all tended to be Masters, or at least experts. By their standards Turing was a beginner, as was Michie. They were in fact evenly matched and used to meet for regular games at a pub in Wolverton. Turing developed his ideas on thinking machines quite extensively during the war. According to Michie, the fundamental notions which were discussed then, and which originated with Turing, included the idea of look ahead, of backing up by the minimax rule, of using an evaluation function to assign strategic values to the terminal nodes of the look ahead tree, and the notion of quiescence as it would now be called. Turing called them dead positions, as a criterion for cut- off of the look ahead process. His first paper on the topic of thinking machines was in fact prepared a year or so after the end of the war, but not published until many years later”.

Coombs

I remember him taking part in a debate on the possibility of intelligent machines.

Randell

After the war?

Coombs

After the war, yes. I must tell you this if you don't know it already; I think this is most important. I became involved in the intelligent machine field, not at that time but many years later. I was off this sort of work. I made MOSAIC, the computer, largely using these wartime techniques that we'd invented, and then I was off doing quite different sort of work until eventually the Post Office round about 1960 or so '63 - decided it wanted to automate its reading of letters, reading postal codes and sorting automatically, and I was put in charge of that work. And I rapidly decided, having looked at the problem, it wasn't just a question of character recognition; it was much more fundamental. This was a development of machine intelligence and I became involved then in machine intelligence, and in the course of this - and this is what my work for the last ten years has been - in the course of this I did come upon Turing's original definition. When you come to define intelligence you see, intelligence is an extraordinarily difficult thing to define. As soon as you explain it you explain it away; as they say, you can't define it; it's one of these peculiar things. Now before you make an intelligent machine you've really got to know what it is you're going to make and so you've got to know what an intelligent machine is, and you find you don't know because you can't define intelligence. Well Turing realised this difficulty and he defined intelligence in a machine in a rather, very, very interesting way. Do you know this definition?

Randell

The Turing test of the conversation . . . . .

Coombs

The two machines - you do know - you all know it so I don't need to tell you this one do I? Do you?

?

I think a lot of people do.

Coombs

Everybody does? Well the interesting thing about this particular - does anybody not know it?

?

I don't know it.

Coombs

All right, I might as well . . . . .

Evans

But in any case, you must say it's a test of thinking and not of intelligence.

Coombs

Thinking indeed, well all right.

Evans

They really could be totally different, in fact almost certainly are.

Coombs

Well all right. I'm not so sure about that Chris. Well let me tell the story anyway. He defined it in this way. Imagine yourself playing a game. The thing is, you are in a room and in another room you are in communication with something. It may be human or it may not, but it's in communication with you, probably through a teleprinter link so that you can't deduce anything about it from its voice or anything like that, but you are in communication with this thing in the other room, and you speak to it on the teleprinter link and it speaks back, and then you speak to it again and it answers you and you have a conversation with it, and he gives an example of the conversation which goes something like that. “In your poem” - you say to it, “In your poem you talked about 'Shall I compare thee to a summer' s day?’ Would not a winter's day be just as nice?” And you get a reply, “No, winter's not a pleasant time of the year. Nobody would like to be likened to a winter's day”. So then you say to the thing, “Oh but some parts of winter are nice; Christmas is nice; Mr. Pickwick wouldn't agree with you”. To which the thing replies “Oh but then Christmas is a special day, not just winter; that's not the sort of thing we're talking about”. And then the conversation goes on like this, you see. Now Turing says if at the end of a certain conversation with this thing you cannot decide whether what you're talking to is a man or a machine, then it's reasonable to call that machine an intelligent machine.

Evans

No.

Coombs

All right, it's reasonable to call that machine a thinking machine; okay, I wouldn't argue about that. You would call it a thinking machine. Now that was his definition. Now the funny thing about it is that that sounds very reasonable except that it's being done by machines that do not think, and one of the leading exponents of the art of doing it with machines that can't think is Chris Evans down there. You have machines to which you talk and they reply and you don't know that they're not human.

Evans

Yes, I think the - I've always thought that was a very important paper of Turing's, mainly because he puts forth a number of arguments which indicate how difficult it is for one to argue that a machine couldn't think; that's the important thing about the paper I believe.

Coombs

Yes, I agree.

Evans

I don't think his criterion for deciding that that's a thinking machine was necessarily very good because you can simulate this quite well but what he was really trying to point out, I believe, is that the only real way you can judge whether something is thinking or not is by having some kind of conversational exchange; I'm sure that's correct. That conversation would be in writing or talking.

Birkhoff

We can discuss artificial intelligence, but I would throw out for everybody's consideration two points which I made in an article on mathematics and psychology I wrote for SIAM Review in '69, namely, first of all, all this emphasis on verbalism, teletypes and games probably warps the role of human intelligence. Secondly, I have one line from a Jamaican song which is 'Your daddy ain't your daddy but your daddy don't know' which any human being knows what it means, and I defy a machine to use principles of programming to decipher it.

Randell

All I did was put on the record, or at least let you know how early Turing - something else that Turing was doing and how early he started it and you can also see how great and lasting an effect he has had on certain people, more specifically Donald Michie, and that the work then, in 1942 and '43 was obviously . . . . .

?

Well actually Jack Good also wrote a sixty or seventy page paper on artificial intelligence.

Randell

Another topic if you'd like is - well I've listed it here as 'The American Scene' because it was my attempt to summarise what people who were working in, shall I say, similar organisations or at least on similar problems, in America during the war, told me in an attempt to help me put the COLOSSUS into perspective. In fact I would also like to make a slight correction to something that I said yesterday. In my paper I say 'It is unclear to what extent scientists and engineers working at Bell Labs, IBM and elsewhere in the States on problems similar to those on - were in touch with the work of Flowers and his team, but there is no evidence at all of American involvement in the design of COLOSSUS. Just as you were quoting from the published literature it is the case, though I cannot vouch for it, that Donald Michie in the two-page article reprinted in my book states that, and again I'll quote if you don't mind, 'During the later stages of the project several members of the U.S. armed services were seconded at various times to work with the project for periods of a year or more '.

Coombs

That's what I tried to say yesterday and you stopped me. It is absolutely true; there were members of the American armed forced working with us in Bletchley at that work, and very interested, very keen, helping, cooperating totally, even to the extent of saying “Look, wouldn't a machine like this be useful?” and we said “Yes so we went and made it”.

Randell

It just switched itself off. *<perhaps referring to another recorder which can be heard going “clunk” when it ran out of tape?>*

Coombs

Since you said it why shouldn't I? They were there. Co-operation was total, perfect, complete and very happy.

Randell

I do not vouch for the accuracy of that statement.

Coombs

Well I vouch for it.

Randell

Let me go back to . . . . .

?

There's also a separate, unclassified, record that does, on the American side . . . . .

Randell

One large relay machine was built by S.B. Williams at Bell Labs. The machine was quite flexible but it had no arithmetic.

Coombs

And it was called Jack (?)

Randell

Williams, in fact, built most of the Bell Labs series of relay computers and the existence of his machine had at least a small influence in the decision to develop the early ballistic computers. An American machine which in concept was similar to the Heath Robinson, and which preceded it, was developed by Vannevar Bush, starting in 1936. Bush is, of course, famous for, amongst other things, his invention in 1930 of the differential analyser but he also worked on digital devices. In a set of memoranda written in 1937 and '38 he proposed and investigated some of the design problems of a program-controlled, electronic digital computer. This work led to a research project at MIT, the rapid arithmetical machine project, sponsored by the National Cash Register Company, in which various basic electronic circuits such as registers and counters were developed. Another project at MIT, sponsored by Eastman Kodak and NCR, grew out of a device, the Rapid Selector, that Bush had invented in 1936. This device was intended for the automatic retrieval of photographic copying of information held on reels of 35mm. microfilm using photo-electric scanning of coded identifiers. Both research groups were disbanded in 1942 because their staff were required for military projects elsewhere. However the Rapid Selector group, which was led by John Howard and included Lawrence R. Steinhardt, had been working on Bush's Heath Robinson-like machine from late 1940. This machine incorporated electronic counters and two photo-electric tape readers. The tape was apparently backing tape from 70 millimetre photographic film rather than ordinary telegraph tape. Each character was represented by a single hole placed at one of forty positions across the tape. Apparently the machine was linked to more or less standard tabulating machines where plugboards could, of course, be plugged to do a variety of things. Bush's machine was completed by John Howard and Lawrence Steinhardt and it functioned in a desultory fashion for many years. After the war John Howard, along with Howard T. Engström and Charles Tompkins were part of the group that founded ERA Engineering Research Associates Inc. They had all three been in a Navy communications operation and had close contacts in Britain and close acquaintance with Turing. It's been claimed, though without supporting evidence, that ERA under contract to the Navy produced one of the world's first three computers, a powerful top secret intelligent computer known as Machine 13; that was a quote from *Datamation*. In fact this was an electronic computer called Atlas developed under a multi-project Navy contract which was delivered in 1950. It was a single-address machine with twenty-four bit parallel arithmetic and word organisation and magnetic drum storage. An earlier relay version named Abel with the same order code was later handed over to George Washington University. A commercial version of the electronic computer was produced under the designation ERA 1101, this of course being binary for 13. My information is that there were no earlier or contemporary electronic machines in the American communications operations which matched the size or complexity of COLOSSUS. A group of sophisticated American devices operating in about 1942 was based on the use of counting and optical matching techniques rather than complex electronic circuits. One machine used glass plates because of a concern for dimensional stability, later found to be exaggerated, and the others used 35 or 70mm. film instead. One such device involved twenty thousand bits to be represented on each frame of the film. Both Flowers and Coombs vaguely recollect learning about some such machine. Various other machines were developed in the U.S. during the war for related purposes, including ones whose electronic complexity matched, and in fact exceeded, that of COLOSSUS. However, American special- purpose electronic devices which predated COLOSSUS were much simpler. For example, one device which involved the use of electronics for calculation purposes was invented by Arnold I. Dumey. Two versions of this machine, which involved perhaps three hundred valves and which probably post-dated Heath Robinson, were completed. They calculated in real time the expected value of the number of successes in a set of trials plus and minus a certain settable number of standard deviations. Only if the observed number fell outside the calculated limits was the printing of the result permitted. Dumey later had responsibility for a larger device involving the order of four thousand valves, which became operational a year after the end of the war. However there were devices incorporating even more valves. The largest such operational devices that Dumey had any involvement with had no less than ten thousand valves. As he himself puts it, “The most interesting thing about life at this time was the way every new electrical invention was tried out as soon as possible in some new device, yet the only early improvement on COLOSSUS was in a more compact way of holding and running the tapes”. The above meagre details undoubtedly give a totally inadequate impression of the quantity and variety of machines that were developed, and of the importance of the work that was done in the U.S.A. in this field during the war. They are given here merely to buttress the statements I have received from both sides of the Atlantic concerning the COLOSSUS, namely that it had no rivals or precedents as a programmable electronic computer, and that there were no links between it and the ENIAC project. I in no way claim that the COLOSSUS helped ENIAC. Everything I have heard indicates that there was a complete separation.

Mauchly

From what I have heard - I came in late to the session - from what I've heard it sounds like ENIAC could have helped COLOSSUS, but it didn't. The reason I say that is because the problems of reliability of counters and things of that sort that I heard - we too tried out those counters from that book, and if you look at the reports which were written, and were of course classified at the time but declassified now and available with difficulty as far as I know - but you can get hold of those reports of how we tested or rejected and what the characteristics were, and so on, but I like to think there are a lot of things to compare - how the COLOSSUS job was engineered, you might say, and how Eckert's modus operandi was of great similarity when it came to the resistors. Of course our source of resistors was right down the street, so to speak. It was the International Resistor Corporation in Philadelphia which had been started and headed by Dr. Pender, Dean of the Moore School. There was a sort of pipeline there, you know, and it gave us better attention. Because it was a war effort, if we needed any special extra connection we could get attention, and at any rate Eckert could go right down there and watch the devices which were sorting the resistors and say “Well, just put me a box there, a box there, and all the ones that were ten per cent too high put in there and the ones that were twenty per cent too high put in there, and so on, and we'll take them back and we'll label them A, B, C, D, and so forth. In each chassis we will use only the group from this box, box A” he said, “And another, box B, another box C” and so even though we were using cheap resistors in a sense, they were not sorting them and setting them to the specific tolerances; we in effect got that by the same methods as you used. On the other hand we were astounded that one of the things that is quite different here is that two hundred microseconds was our total addition time and the way we were able to operate with these shorter pulses I'd say in large part was because every counter had what we called a pulse former. No matter what kind of signal came in, if it observed very wide characteristics, if it fell in that general class it would produce a pulse which was exactly the same within very close limits for the counter itself to respond to, and it was my understanding, and still is, that this was one of the greatest contributions which Eckert made when he was studying those counters to realise that most of the poor performance of counters in the past had been because everybody was expecting an answer to any kind of a pulse. It was a much better performance going up to two hundred thousand pulses per second and two to one variations in voltages and all those things. It could get(?) all that performance very much by putting pulse formers in. From what I learned I gathered that you standardised the pulses in a certain form but that what you really were trying to do was work to a low speed requirement. The highest speed you could get reliability of the paper tapes became a limit which you did not attempt to surpass, as far as the electronics went.

Coombs

Effectively yes, because there's no point.

Mauchly

And one of the things people do in testing tolerance to develop(?), and you did it too, was to nevertheless test the electronics at limits much wider than this.

Randell

I'd like to take up your point on registers just for a moment to make a general point. I think this illustrates how completely inadequate it is to have a naive view of history as chronology, an assumption that if something was done it would be invented in only the one place. In all probability where the need is similar and you've got people of equivalent calibre then you're going to find a lot of parallel invention, and that is no discredit to anybody, and what we are finding out here all week is a lot of parallel invention and a lot of useful interaction. And I'm sure you are right; it's a great pity that there was not interaction, for example, between COLOSSUS and ENIAC.

Mauchly

I would just like to end on a note that these reports on ENIAC being available, although with difficulty you might say, there was no legal or military security bar. It seems to me that if someone would take the trouble they might get a lot of interesting things in comparing these two things as regards the modus operandi of the engineering, regardless of what was being engineered, and not worrying about is the COLOSSUS programmed like ENIAC, no, and all those things. I'm not trying to judge the end result but judge the reliability engineering part. And the closing statement which (?) me was that in the '30s when I was trying to build an analogue harmonic analyser, which I did build and it worked and so forth - very useful for analysing atmospheric tides - that I couldn't afford quality precision resistors. I couldn't even afford to get IRC or somebody to select things to five per cent tolerance and so forth, so I bought a whole quantity of it and what I did was to match them. If I wanted a five thousand Ohm resistor I took two ten-thousand Ohms and I kept testing highs and lows until, putting them in parallel, I got what I wanted.

Coombs

Yes.

Wheeler

Is it possible to say how many stages of logic you went through for each reading, for each clock pulse?

Coombs

I think the figure that you've got in your paper, and I don't know where it came from because I can't make it come out, but the figure that he's got is that you could do a hundred and twenty Boolean operations. Well I don't know; I don't know where that figure came from; I can't imagine but I'll accept it for any one clock pulse at - what is it - at two hundred microsecond intervals there were up to a hundred Boolean operations to be correlated, in parallel really.

Randell

In series and in parallel.

Coombs

These would be parallel. Well the series limit was always the limit of the speed of the tape. This is quite right and we ran it at twice speed to make - well we knew the circuits and could cope - we had reached the stage in this design - I was telling somebody at teatime - which was quite amusing, we had reached the stage when we could design circuits and have them made - we never tested them - you see we wanted to do so and so we designed the circuit and put it together and it worked. We knew it would work, and it did work; it never failed. And after the war I caused some derision actually at Dollis Hill when we were on a new project and we sat round a committee and saw what we were going to do and this sort of thing, and I said “Well, I think we'll do this and the next thing” and they said “Yes, well that's all right”. And I said “Well I'll make that system shall I? You don't want to test it, do you?” And everybody looked at me in horror for this had never been heard of before - a new project, build a whole lot of circuits, a whole machine and not test any of it before you put it together. But this was a relic of the wartime experience, of building COLOSSI on such a system that we never tested anything. It always worked first time, and this is quite surprising because it's never happened since. It's interesting Mr. Mauchly, John Mauchly there, that you mention this point about speed because I would like to tell you - although I think it may be too late tonight, we may be able to squeeze it in sometime tomorrow - how afterwards when I got involved in the building of a computer - Turing's Mark 7 ACE - which was given to me to build for the Ministry of Supply for a special job where the NPL itself were building Turing's Mark 5. I had the building of a computer, and I used COLOSSI principles throughout for the making of this, except that with post- war valves and with more power and with more speed required the computer that we built had to work. We found that a good speed was about seven hundred kilocycles so that our pulse time was about one and a half microseconds as opposed to two hundred microseconds on the COLOSSUS. So we had to adapt all our techniques to this and we did it in the appropriate way, but what we came up against was this fact, that we believed in pentodes, not double triodes and things like that. We believed in pentodes; we believed in many valves. Put as many as you want in, they'll all work. The result was that the machine we built was big and it consumed sixty kilowatts, actually a lot of heat. But anyway, it was a very big machine and some of the cables were two hundred yards long, and we had the problem of a pulse machine working in pulses, at a pulse period of one and a half microseconds and the time taken to travel down one of these cables itself was one microsecond. So what were you going to do about that? The speed limit was the time taken to go down a cable, not the speed of a tape, so again we had this problem to solve. How do you manage to cope with things like that? And we did it, as you were saying, before we did any operation on any pulse. We always reshaped it, make it a nice square pulse and all the other pulses it was reacting with were made nice square pulses and there was a 'pink' with a clock pulse and got the answer out, you see, and this was fine. But the problem is, of course, that the clock pulses themselves get delayed as they go round so what do you do about that? And we invented a technique to cover this which as far as I know is unique, which is obsolete in the sense that transistor machines are so much smaller that the lengths are not like this and they do not take the time, but which nevertheless may be important to somebody later when transistor machines work so fast that even the short distances there become important as a time factor.

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It's already a commercial problem.

Coombs

It's already come: has it?

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Where the physical sizes are so large that the . . . .

Coombs

May I then volunteer to say that sometime when you've got a blackboard available I would like to draw you the system that we used to do this, because what we did was invent a circuit which, as the accent at that time was breaking the sound barrier, we called it the system that broke the light barrier because we made synchronising pulses appear instantaneously at all points in the machine without any delay between them. Now if you don't believe that you're quite right, but I'll tell you why it looked like that with the blackboard sometime. I think it's a bit late tonight to start doing it and I haven't got a blackboard anyway.

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It's done with mirrors.

Coombs

We didn't do it with mirrors; we did it with very clever little things . . . . .

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Delay lines?

Coombs

No, not delay lines; we didn't do it with anything as crude as that. We were very, very clever, and nobody's ever used this system except us. I'd like to tell you about it.

Randell

Are there any further questions? Unless there's anybody with any burning comments or questions? Okay.