Replicating the Manchester Baby: Motives, Methods, and Messages from the Past

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The University of Manchester's Small-Scale Experimental Machine (SSEM), known as the Baby, was rebuilt as a replica to celebrate, in June 1998, the 50th anniversary of the running of the world's first stored program. This article explains the background of the original Baby, and why and how a replica of it was built. The article concludes with some of the lessons learned from the project.

When the Computer Conservation Society (CCS) was formed in 1989, it brought together a number of people interested in the early days of the computer industry, but who for the most part had not previously been aware of each other's existence. Personal networking at early formal and informal meetings of CCS members at the Science Museum in London sparked enthusiasms, ideas, plans, and ambitions for practical computer history projects of a serious nature. Initially, the main focus was on conservation, and restoration to working order, of some of the significant computer systems in the museum's collection. This activity provided an opportunity for retired engineers to re-hone their former technological skills while learning about history and curatorial integrity. In parallel with those efforts there was an interest in recreating early computers by software simulation, using modern and relatively high-performance host platforms. And a few members were fascinated by taking simulation to its ultimate conclusion: building authentic physical replicas of the target systems.

Motivations for reconstructions

The first historical construction to come to our attention was the project to build Babbage's Difference Engine No. 2, then under way at the Science Museum in London.[1] Conversations with Tony Sale, the first CCS secretary, revealed that he planned to build a replica of Colossus, aided by his contacts in the code-breaking field. He had already replicated and demonstrated early cathode-ray tube (CRT) storage using modern electronics and a bench oscilloscope.[2] During these conversations, we discussed the possibility of replicating other early computers, in particular the Cambridge EDSAC and the first Manchester computer, the forerunner of the Manchester Mark 1. None of these machines survive in physical form, and replication would involve reconstructing them from surviving documentary and oral sources. Naturally, our interest was in early British computers, because we were more likely to know the relevant original pioneers.

Several factors motivated us to undertake the Manchester Baby project. One of the activities within the CCS and the Science Museum was recording and collecting taped oral history interviews with pioneers, and it was clear from this material that access to pioneers to answer questions about their early endeavors would be valuable in achieving an authentic replica. On the other hand, the actual building of a replica would require technical skills that were mainly possessed by the generation of engineers who happened to live through the relevant times. So there was a *timeliness* for such projects dependent on particular people, most no longer young, with appropriate knowledge and presumably, because they were likely retired, with time to spare.

Nostalgia also figured as a motivation. It seems to be a commonplace that every generation bemoans change. For engineers, the juggernaut of ever-changing technology presents a constant problem of learning new things and a reluctance to forget the old, in case the old may turn out to be useful. Of course, this is likely to be more noticeable among people who like to look to the past as a way to put the pres-

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The Principle of CRT Storage

In a cathode ray tube, an electron gun at one end projects a finely focused beam of electrons toward the fluorescent screen at the other end. Where the beam strikes, the screen phosphor glows, and deflection of the beam by electric or magnetic fields causes the glowing spot to be moved to anywhere desired on the screen. The principle is familiar in the screens of our television sets and PC monitors.

Under certain conditions of beam accelerating voltage and beam current, not only does the screen glow but the incoming electron beam dislodges electrons from the atoms of the phosphor. These secondary electrons move to the anode of the tube and are lost. If the conditions are correct, more secondary electrons are liberated than beam electrons, perhaps 50 percent more. Consequently, at the bombarded spot there is a net loss of electrons and the spot becomes charged positively. This action takes place in less than half a microsecond from the time the electron beam is switched on. The charge is slow to leak away because the screen and the interior of the tube are very good insulators, and if the beam is switched off, the positive charge remains. The charge may stay in place for more than a second, and it is this that constitutes the memory of the CRT. By convention, a charged area is regarded as a 0 and an uncharged area as a 1.

A piece of wire mesh connected to a high-gain amplifier is pressed to the outside of the glass screen of the CRT. When the beam is switched on, and the spot acquires its positive charge, capacitive coupling from the spot through the glass to the mesh causes a small positive signal to be

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ent into perspective. But it must be a powerful motivation, as witnessed by the large number of people who pursue an interest in other technologies such as steam trains and old aircraft. There is something quite exciting about reliving the experiences of people who brought about important innovations.

A further motivation was *education* and proselytizing. I am constantly dismayed that engineering achievements receive scant attention by the bulk of the population, which is led by the media and which relates to the degree of respect accorded to engineers. It is perhaps reasonable to ignore an innovation when it is new and future ramifications cannot be foreseen, but it is not reasonable to ignore an innovation when it has proved a major influence. The availability of a replica to look at and touch must be a valuable peg for all sorts of educational approaches to attempt to convey a balanced historical view of the past.

Discovery, and the hope of finding something new to say about the original system, was also a factor in our reasons to build a replica. There is curiosity about the details of an object that is not necessarily satisfied by study of its description in any surviving documentation.

Finally, there was the powerful motivator that building a replica is *fun* to do, and this gave the project team a focus, a social context, and a chance to stretch physical and mental skills.

Historical context

The history of the development of the original first Manchester computer has been well told.[3-5] Only a summary will be given here to place the replica project in context.

From the perspective of the UK, World War II caused an upsurge in electronics know-how as a result of developments in radar and communications. Much of the radar work was done at the deliberately misleadingly named Telecommunications Research Establishment (TRE). There, F. (Freddie) C. Williams and his small team were the experts in electronic circuit design. Williams was invited to visit the Massachusetts Institute of Technology in 1945 and 1946 to edit and contribute to part of the Radiation Laboratory series of books (known popularly as "the five-foot shelf") on radar techniques. While in the US, he viewed experiments in which researchers attempted to store radar images using CRTs, work with which he would have felt entirely at home. He also saw the ENIAC and heard about the research toward an electronic memory system for that machine. He returned to the UK after his second trip with an idea as to how to use a CRT as a calculating machine's memory device.

By the end of 1946, Williams and his colleagues had successfully stored one digit and had filed a provisional patent for their method. At this point Williams was appointed to the Chair of Electro-technics (now Electrical Engineering) at the University of Manchester, apparently with the blessing of TRE, which wanted him to continue the CRT memory research. He was accompanied by one of his colleagues, Tom Kilburn, a mathematician-turned-engineer who was on loan from TRE. In a late-Victorian-era university laboratory originally called the Magnetism Room, they developed the storage system, with Kilburn doing much of the hands-on technical work. By late 1947, they had a working high-speed electronic memory storing 2,048 bits, and Kilburn issued a widely read report fully explaining the technique (see the sidebar, "The Principle of CRT Storage").

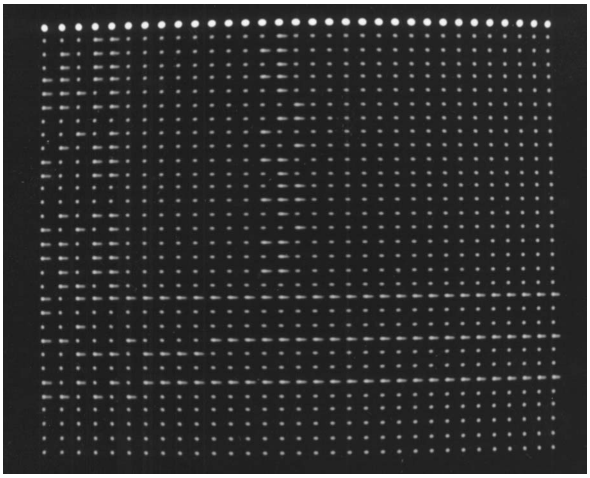

Figure A. A program stored as dots and dashes on the screen of the Store CRT of the replica SSEM. For each line, the least significant digit is on the left. The top line is bright because it is being accessed 32 times more often than the other lines.

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detected, which is turned into a robust signal in the amplifier. If the beam is turned on at a spot that had already been charged earlier, then a small negative pulse is detected, corresponding to the arrival of the electron beam in the vicinity together with no change in the spot's state of charge. Thus uncharged/charged, 1/0, can be detected according to whether the amplifier output is positive or negative at the time of switching on the beam.

Writing a 0 is achieved by bombarding the spot as just described. To write a 1 (no charge) at a spot that was previously charged, the beam must be made to fill in the charged area. Of a number of ways to do this, the Small-Scale Experimental Machine (SSEM) used the dot-dash method. The technique was to switch the beam on (which enables the current state of the spot to be determined), and then if a 1 is to be written, to deflect the beam slightly (say, a millimeter) to the side on to an uncharged area. The secondary electrons thus liberated are attracted to the positive spot and discharge it. There is adequate time when a spot is read to decide whether to move the beam to rewrite a previous 1.

By deflecting the beam, an array of spots can be addressed, each of which can be a 0 or a 1. Provided each spot is visited within say half a second of its last visit, so that it can be refreshed, the CRT store retains its charge pattern and hence the written data. In between refreshes, the beam can be deflected to randomly access any spot to retrieve the data according to the needs of the program. The alternating phases of systematic refreshing and random access are called the Scan and Action phases. The SSEM used a square array of 32×32 spots, yielding a 1,024-bit memory. It is interesting that the techniques of orthogonal addressing, charge storage, and refreshing are all present in today's dynamic RAMs, which can carry millions of stored bits on 25 mm^2 of silicon.

Although their work in the electrical engineering department was completely independent of outside influence, Williams and Kilburn were nevertheless encouraged by the Mathematics Department's Max Newman, who secretly knew about the Colossus code-breaker machine and was familiar with the work of Alan Turing. Newman wanted a computer in his department and could see that the Williams–Kilburn work might lead to one. Newman's receipt of funds to establish a Royal Society Computing Machine Laboratory was not used by Williams (who was fully funded by the university and TRE), though he later appropriated the name as a tag for the Magnetism Room.

Although the CRT storage system was working in late 1947, it had not been proven to work "in the hurly-burly of computing," as Kilburn put it in one of our conversations. He needed a stringent, dynamic tester for it and resolved on a very simple computer as the appropriate test bed. With the help of Geoff Tootill, who had also joined the team from TRE, the three men designed and built the necessary and barely sufficient equipment to make a general-purpose computer out of their storage system. (For functional structure details, see the "Functional Structure of the Baby" sidebar). They did this work from late 1947 into the first half of 1948, and by June 1948 the machine was complete but not yet working. Tootill has characterized the period as being like a wartime radar crash program: intense activity to get the job done without too much regard for aesthetic niceties. At about 11:15 a.m. on Monday, 21 June, a program written by Kilburn executed correctly, the first time that a stored program worked in an all-electronic computer.

Over the next few months, the machine was extensively enhanced both in capacity and functionality, and what was originally known as the Small-Scale Experimental Machine (SSEM), and informally as "The Baby," gradually evolved into the Manchester Mark 1 computer.[6] Figure 1 (on page 48) shows a familiar photograph of the machine as it was in about April 1949. The size of the team doubled when postgraduate researcher Alec Robinson and two research students, "Dai" Edwards and "Tommy" Thomas, joined in late summer 1948. This evo-

Functional Structure of the Baby

The CRT memory held 32 words, each of 32 bits, and could be loaded either from the push-button typewriter or from the output of the subtractor. As Figure B shows, program instructions from the store (memory) went to the control CRT via the adder and normally appeared on the present instruction (PI) line. Operands from the store went to the accumulator via the subtractor. The output of the subtractor always went to the accumulator. The program counter (CI) was also held in the control CRT.

The output from the control CRT (either PI or CI) was fed serially to the 8-bit staticisor, which held the instruction during execution. (The staticisor was a set of eight 2-vacuum tube flip-flops, three for the operation code, five for the operand address.)

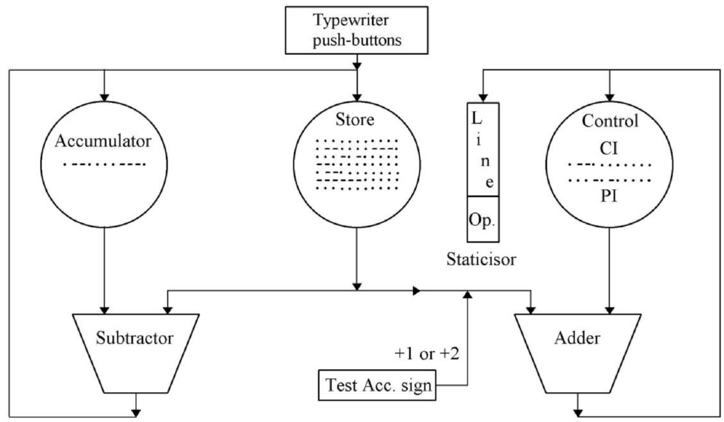

Figure B. Simplified schematic of the SSEM.

The 5-bit operand address selected the Y-deflection of the store CRT, and thus the addressed line in the store. The 3-bit operation code was used to gate the appropriate functions for the current instruction. The result of operations could be read directly from the face of the appropriate CRT, or more conveniently from a monitor CRT located at the operating position.

Seven operation codes were available:

Op. Code	Mnemonic	Description
0	s to C	Jump indirect
1	s + c to C	Relative jump indirect
2	–s to A	Load negative
3	a to S	Store accumulator
4	a – s to A	Subtract
5	–	Not used
6	Test	Skip next if Acc is negative
7	Stop	

Uppercase letters in column 2 refer to the device; store, accumulator, or control. Lowercase letters refer to the contents of that device. Thus, Op. Code 1 in the table means the contents of the store line plus the contents of the control are passed into the control.

The basic rhythm of the Baby was:

- CI line + 1 to staticisor and to CI line
- Instruction from store to PI line
- PI line to staticisor
- Operand from store to accumulator

The subtractor allowed addition of operands (a + b = – (–a –b)), whereas if there had been only an adder, subtraction could not be done.

lution has been succinctly described by Lavington[3] and by Napper.[7]

The Baby machine had already vanished by late 1948 in the sense that it had been heavily modified and enhanced into the prototype of the University of Manchester Mark 1 computer, and it was this enlarged machine that performed useful work through 1949 and 1950. All the equipment was scrapped at the end of 1950, ready for the delivery of the properly engineered version, the Ferranti Mark 1. Just one of the original bare steel racks has been preserved at the university, though its provenance seems to be undocumented.

Some of the early programs that ran on the SSEM in summer 1948 are described by Shelburne and Burton; in particular, there is a description of the best estimate of the first program's code as retrospectively reconstructed by Kilburn and Tootill.[8] The occasion when that program first ran correctly is regarded as a key date in computer history, and it was the defining moment for inspiring the replica building project.

50-year challenge—Goals and objectives

By late 1994, the 50th anniversary of the first program's running was already on the horizon. Encouraged by CCS colleagues, I wrote a project

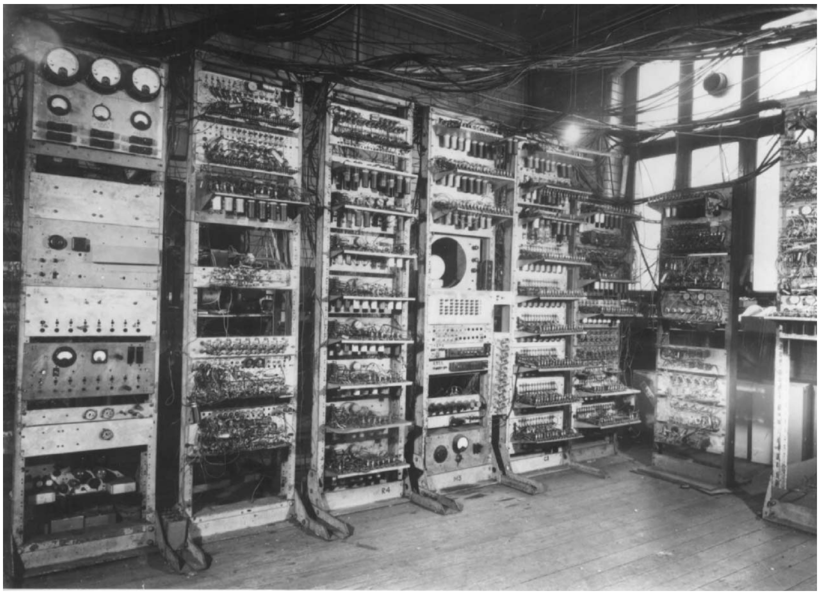

Figure 1. The Manchester Mark 1 prototype, circa April 1949. (Courtesy of the School of Computer Science, the University of Manchester.)

proposal aimed at an internal audience, describing the steps required to build a replica of the SSEM in time to celebrate the jubilee. The target would be a machine as near-identical as possible physically and functionally to the original machine as it was on 21 June 1948, and able to execute the original program. The proposal made several gross assumptions: that it would be possible for us to find the old parts; that there was sufficient available detailed information from which to deduce the design as it was in June 1948; and that construction would be carried out by enthusiastic CCS volunteers, possibly with some paid-for structural metalwork.

I did a substantial amount of preliminary investigation at this early stage to make sure that the idea was technically viable. A crucial source was a private notebook, belonging to Dai Edwards, containing numerous detailed circuit diagrams. Edwards had given a photocopy of that notebook to Tony Sale, who had passed it on to me.

The proposal articulated a goal and a set of objectives. The goal was to build the replica, and run the first program on 21 June 1998, exactly 50 years after the original event. The objectives were intended to satisfy some of the motivations we might have for doing the work and included:

- present the replica as a tangible tribute to the largely unsung pioneers in Manchester and elsewhere who contributed so substantially to what came to be called the Information Age,
- recognize that the Baby signaled a particular triumph of innovation in Britain,
- remind generations of people of what the old technology was like, and
- make the machine as authentic as possible.

The proposal came to the attention of the University of Manchester's Computer Science Department staff, who enthusiastically welcomed the idea because it chimed with plans they were already formulating to host a major conference to celebrate the 50th anniversary. At that point, professors Cliff B. Jones and Frank H. Sumner were proactive in getting the project recognized as something that should be done at the university. The Museum of Science and Industry in Manchester was also supportive at this proposal stage because it was foreseen that the replica should eventually be preserved in a museum. Although I had an ambition that the replica should go to London's Science Museum, it became apparent that its more natural home would be in Manchester, the location of the original work, at the Museum of Science and Industry.

Methods

Successfully replicating the Baby—and rerunning the first program—would be a project involving many methods, both familiar and unfamiliar. Many of these methods resulted from the use of obsolete technology in a modern setting, and of the nonindustrial, voluntary, low-cost environment.

Planning and organizing a voluntary project

Enthusiasm for the project's challenge was so high that at the start the question of funding was subsumed as a problem to be solved later—a working plan was seen as the first priority. We had just three and a half years before the deadline, a date that could not be changed. To keep the various interested parties on track, a small steering group was formed in March 1995, chaired by Cliff Jones. The group included Peter Hall, a former director of ICL and chairman of the local group of the CCS; Jenny Wetton, curator of science at the Museum of Science and Industry in Manchester (MSIM); Frank Sumner, former director of the Manchester Computing Centre, which provided the university's computing service; and me. The group's composition changed slightly during the project. Two notable changes were Steve Furber, who took over as chair when Jones moved to the University of Newcastle-on-Tyne, and later the addition of Tom Hinchliffe, managing director of ICL High Performance Systems at nearby West Gorton. I was confirmed as project manager. The steering group's quarterly meetings enabled me to report on progress and highlight problems, and let the other members feed back a coherent picture into their own organizations so that the replica project could be coordinated with the increasingly ambitious celebratory plans for June 1998.

The overall plan as outlined in my proposal featured a demonstration apparatus, later called the feasibility rig, which would be built as soon as possible to show that a CRT memory could be made with period components and original circuit designs. It was assumed that the rig would contain about 40 valves (vacuum tubes) in one 19-inch-wide rack, about 6 feet high. This was a single-handed task for me as the project manager, and was to be ready by the end of 1995. During the same year, investigations into any available documentation of the original SSEM, and into the availability of obsolete electronic components, would be carried out. Thereafter a team of volunteers would be recruited to carry on detailed investigations into all parts of the SSEM and to physically assemble the machine to be ready by the end of 1996. The team would then devote 1997 to making the machine work (that is, solving the problems not revealed by examination of documents), and leaving the first half of 1998 as contingency time before the goal date of 21 June 1998. So the very simple plan evolved:

- 1995—Study the 1948 design and acquire parts
- 1996—Design and build chassis and assemble the machine
- 1997—Make it work
- 1998—Consolidate and meet the goal

This plan worked quite smoothly. Establishing a volunteer team turned out to be pleasantly easy. A group of CCS members—including Adrian Cornforth, George Roylance, Ken Turner, and Keith Wood, and led by Charlie Portman—had spent almost a year carrying out the physical conservation of an incomplete Ferranti Pegasus computer (1957 vintage) on display at the MSIM. Adrian is a busy software engineer with an interest in the history of early computers. Charlie was an ICL Fellow doing advanced systems research in ICL, in the few years before his scheduled retirement. The others were all retired engineers from ICL and had known each other, as well as Charlie and myself, reaching back to the days of vacuum tube computers in the Ferranti Computer Department in the 1950s and 1960s. George had worked on the Manchester University Atlas computer development and had been a voluntary worker at the museum for some years. Ken had worked on magnetic drum development in those far-off days, and now taught computer studies part-time, while Keith had been a development engineer on projects ranging from vacuum tube computers to artificial intelligence.

The Pegasus conservation work was carried out on Tuesday evenings at the museum, which has a well-organized structure for volunteers to look after museum artifacts such as railway locomotives, aircraft, and textile machinery, among others. After conserving the Pegasus, it was agreed that restoring it to full operation would be inappropriate because there was already a working Pegasus in London. So, by early 1995, this group was a ready-made team looking for more work.

My friendship with Charlie and the others meant that it was natural that he and his group should be invited to form the nucleus of the SSEM replica team. I also asked Bill Purvis—who we vaguely knew through his attending CCS evening lectures, and who I found had a mutual interest in cave radio and electronics (speleonics)—if he would be interested. Bill was also a software engineer, who at the time worked at the Daresbury High-Energy Physics Research facility and who was an enthusiastic and versatile engineer. All these people met for a Sunday session at my house in late 1995 to get introduced to the project and accept their different tasks and commitment to the overall goal and objectives. Adrian had less experience of hardware construction but produced at least one chassis for our project. In particular, he took on the parallel crucial task of creating, developing, and maintaining the original version of the CCS Web site, which included our replica project.

Establishing credibility and funding

Although the steering group and I were highly confident that the project could succeed, it was clear to everyone that getting CRT storage to work again remained the highest risk. The purpose of the feasibility rig was to eliminate that risk as well as to convince supporters outside the project that we meant business. The rig (see Figure 2, next page) consists of a single rack with several selected chassis corresponding

Figure 2. The feasibility rig in the author's office prior to transporting to Manchester. (Photo by Christopher P. Burton.)

as closely as possible to those in the SSEM. The aim was to be able to store one or two lines of 32 bits, possibly with a half-adder so that we could observe a counting pattern. The minimum circuits required were a timing pulse generator, horizontal time-base generator, high-gain CRT signal amplifier, recirculation gate circuit, and the CRT itself. These were supported by appropriate high- and low-voltage power supplies and some control switches. Supplementary circuits included a flip-flop to make the CRT scan two lines alternately, and a half-adder chassis.

The feasibility rig was highly successful, and was demonstrated at the high-profile launch of the various celebratory plans in Manchester Town Hall in March 1996. By that time, the authorities of the city of Manchester were also planning to contribute to the jubilee activities by coordinating "Digital Summer 1998" in the city, with various cultural and popular events. After this public appearance, the rig was enhanced in various ways to make it a useful test bed for training, and also as a signal source.

In mid-1995, a presentation was given to ICL's Tom Hinchliffe, at the West Gorton plant, which was the descendant of the former Ferranti Computer Department that had engineered the University Mark 1 to make the Ferranti Mark 1 production computers. After listening to our plans, supported by fairly detailed costings and risk assessments, Hinchliffe generously offered sponsorship from ICL for the project. This was to consist of free provision of workshop resources and the purchase of any required materials, as well as incidental expenditures. This timely support allowed me to concentrate on planning and on technical matters, unencumbered by problems of seeking further funding.

Establishing the original logical and physical design

As its name implies, the SSEM was very much experimental. The pioneers had no need for formal engineering drawings. Their working documents were a set of hand-drawn schematic circuit diagrams on a table (jokingly called Tom Kilburn's Office), in the corner of the laboratory, together with their personal notebooks. If a chassis had to be made, it was left to the technician in the workshop to cut sheet metal and physically lay out the components. The machine was constantly being modified and added to, as were the diagrams that always represented the current state. Those circuit diagrams no longer exist, so we have had to rely on secondary sources, described next.

Apart from the CRT storage patents and Kilburn's CRT report mentioned earlier, the earliest surviving material is a notebook that Geoff Tootill kept and which is currently preserved in the archive at the MSIM. The notebook entries begin with a "First attempt at a BLOCK DIAGRAM" dated 4 June 1948 and continue through to January 1949. The notebook has no complete circuit diagrams, but does contain fragments of circuit designs and many notes about the instruction set, programming issues, and machine operation. This notebook is the only contemporary extant detailed material regarding the events of 21 June 1948. An earlier notebook kept by Tootill was destroyed in a fire some years later.

In August 1948, Alec Robinson made a copy of the computer circuit diagrams in his own notebooks, which he has kept and which survive. Copied in a hurry, they vary in quality and completeness but are probably the nearest to the state of things in June. Robinson had been developing a multiplication unit using a CRT in an adjacent laboratory, and he made the copies because he needed to catch up with the SSEM's current state prior to attaching the multiplier to the computer.

As mentioned earlier, research students

Thomas and Edwards had joined the team in September 1948. Edwards meticulously copied the lab circuit diagrams into his notebook, which has survived. Many diagrams are dated, from October 1948 through late 1949. Consequently, they reflect a state of the SSEM after months of changes dating from June 1948. However, the diagrams' completeness, the detailed associated notes on operation, and their delightful neatness (made with pen and ink and ruler, no photocopiers or drafting aids) have made these diagrams the most valuable reference describing the original circuits.

Finally, two important papers that we used as references were published in the *Proceedings of the Institution of Electrical Engineers* in London. The first, published in 1949, was based on Kilburn's report, dated 1 December 1947, which describes the CRT storage system.[9,10] The second paper, "Universal High-Speed Computers: A Small-Scale Experimental Machine," was published in 1951.[11] This paper, which had been an inspiration to me for decades, is now available online.[12] The paper is largely based on Tootill's MSc thesis and contains some of the key circuit diagrams that can be made to correspond well with those in the notebooks mentioned above.

The SSEM's physical design was understood in overall terms. The well-known image in Figure 1, for example, shows the general appearance. The 19-inch Post Office racks were standard items with standard drillings. The chassis construction consisted of a folded sheet metal shelf, containing the vacuum tubes hanging downward and the smaller electronic components above. The shelf was fixed to a 19-inch-wide panel that also carried controls, switches, terminals (binding posts), and connectors. The "front" panels are actually at the rear so that the working electronics are accessible. This form of construction was derived from that used experimentally at TRE.

Although the image in Figure 1 is often described as a photograph of the Baby machine, it actually shows an intermediate stage, beginning to resemble the University Mark 1, and was probably taken around April 1949. There is no known photograph of the machine from June 1948.

A panoramic view of the machine was published in *The Illustrated London News* in June 1949.[13] On my inquiring about that picture, Tootill asserted that it was actually a composite view made up of about 24 separate photographs taken by Robinson much earlier than the publication date, and that the composition had been done by the London Electrotype Company presumably entirely by photographic methods. Robinson still possessed most of the 35-mm negatives of those photographs, and an entry in his notebook showed that they were taken on 15 December 1948. They are the earliest extant photographs of the machine. Figure 3, one of those photographs, shows two shielding boxes each containing a storage CRT. The "haywire" (experimental) nature of the machine is evident.

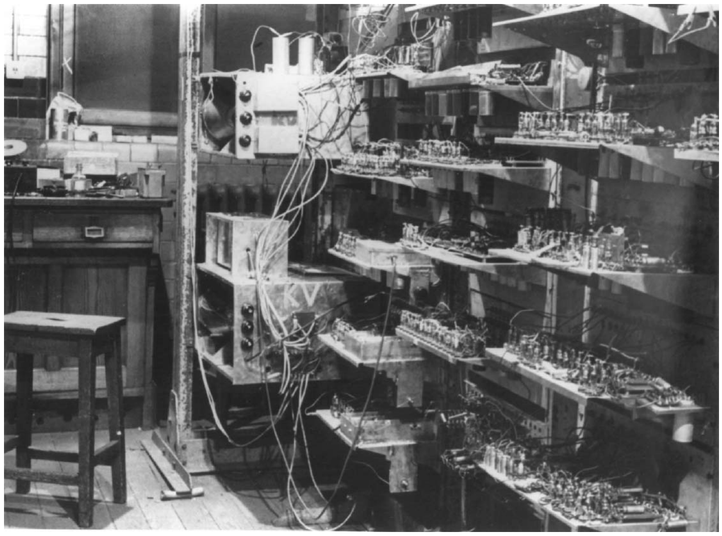

Figure 3. Photograph taken by Alec Robinson on 15 December 1948 showing two of the CRT storage boxes (center). The racks on the right are part of the Multiplication Unit, which had been added to the SSEM at that date. (Courtesy of the School of Computer Science, the University of Manchester.)

Our goal was specifically to replicate the machine as it was on 21 June 1948. The circuit diagram fragments and photographs were the key sources in our achieving authenticity. However, an irreplaceable supplement was the willingness of the original team to recall their memories of the machine. Williams died in 1977, but Kilburn, Tootill, Robinson, and Edwards were all happy to be interviewed, and Thomas—living in Australia—was consulted by email. One interesting outcome of the interviews was that, often toward the end of a discussion, useful bits of information would emerge partly from the interviewee's recognizing some document or photograph that triggered a secondary thought. It seems doubtful if those items would have emerged without the artifacts to do the triggering.

Kilburn and Tootill saw the feasibility rig in operation in March 1996, and they were inspired to try to rediscover the coding of the first program. They put a great deal of effort into that research to make possible the goal of rerunning the first program exactly. They commented that encountering a real working CRT storage system again brought back many memories of the time and that this helped them to establish the authentic code.

Obtaining parts

The replica's authenticity would crucially depend on the availability of original electronic components. The CRTs were known to be type VCR97, the commonest wartime 6-inch radar tube. Many of these have survived in private hands, though of unknown quality, and it was expected that sufficient quantity would be found. Most of the vacuum tubes were type VR91 pentodes (equivalent to the civilian type EF50, designed by Phillips in the late 1930s), and type VR92 diodes (EA50). Again, they were commonplace in 1940s wartime, and enthusiasts would typically have hoarded a dozen or so. We were going to need around 200 VR91s and 400 VR92s. A total of 100 or so of several other types, including the famous type 807 beam power tetrode, were also required. There were no semiconductor devices used in the original.

To our amazement, a number of dealers in England still had stocks of these vacuum tubes. We had the feeling that they had been quietly waiting for 40 years for a serious inquiry to come in. But there was also the sense that they were soon going into the scrap, so we were probably just in time. Cliff Jones made the bold decision early in 1995 to fund from his departmental budget the purchase of sufficient vacuum tubes, at a stage when the project was still being debated. All the vacuum tubes appeared to be new and unused in original packing, dating from 1943 to the early 1960s. It was fascinating to find that the 807s were made by RCA in Philadelphia in 1943, shipped across the Atlantic, possibly dodging U-boats, for delivery to the British war effort, and still in perfect working order, fully to specification.

Smaller components such as resistors and capacitors were more difficult to find because they were more likely to have been discarded as low-value items. Furthermore, these components were more likely to have changed their electrical properties or become unusable with the lapse of time. Amateur radio rallies provided some leads to sources among radio hams, and many people came forward with a bag of resistors saying they had kept them so they could make an audio amplifier when they retired, but that it turned out to be easier to go to the shopping center and buy one. One colleague arrived with large boxes of these small components, unused and rescued from a radio repair shop that had closed. Where an authentic old component was not available, a more modern version would be used, and we would record that it was not authentic. In principle, every section of the machine has a Provenance and Authenticity Statement containing such information, although currently records are far from complete.

Hardware items such as plugs and sockets, screw terminals, vacuum tube holders, and even the correct type of nuts and bolts were tracked down and purchased or donated. The numerous variable resistors were identified from the photographs as Colvern wire-wound types. A virtually identical component is still available from UK-based R.S. Components, a large mail-order component supplier, and these were used for reliability. To my regret, the original rubber-covered "push-back" wire could not be found, so we used a modern plastic-covered wire. With hindsight we should have used a much thicker wire to get a truer appearance, but it is too late to change all the wiring now.

One particularly satisfying discovery was the exactly correct push-button switch used in the so-called typewriter visible just below the monitor CRT in the photographs, and used to insert single bits into a selected word in memory. I spent many hours gazing at the original photograph through a jeweler's eyeglass (Figure 1). In one serendipitous moment, the pattern of holes on the panel suddenly brought to mind a set of five push buttons that I had bought in 1953, and which I still had. Furthermore, I still had the relevant catalog of war-surplus electronic equipment, though the dealer had long since disappeared. The catalog cited a Royal Air Force part number, and the part was recognizable in a photograph of the Spitfire fighter's cockpit: It was a control box for the VHF radio. An inquiry to a dealer in vintage aircraft parts yielded the reply that he had just the number required, though they were 20 times more expensive than they were in 1953.

Surprisingly, the 19-inch racks were hard to find: They have long been superseded by folded sheet steel equipment racks. A call was received one day from a radio amateur who offered two if he could have help retrieving them. He lived in a house in Shrewsbury at the side of the River Severn, and he had used the racks to stop his garden slipping into the river. He said that he was going to move to a new house, so he was happy to let us have them. After sandblasting and painting, they were in excellent condition. Other racks were cut down from some that were surplus to Tony Sale's Colossus project.

The power supplies for the SSEM are something of a mystery. No pictures or documents exist. They were most probably standard 50-

volt, 10-amp telephone exchange modules, as used in Colossus, and indeed in 1948 Williams may have obtained units indirectly from dismantled Colossi. The high-tension supplies of +300 volts, +200 volts, and –150 volts had been obtained by wiring a chain of such modules in series. For the replica it was decided that exact authenticity was not needed; power is provided from a rack containing six modern switched-mode series-connected modules, coincidentally also designed for small telephone exchanges. Approximately 100 amps of 6-volt heater power were also provided, via large transformers formerly used in manual telephone exchanges, and judging from the photographs, probably the type used in the original machine.

Figure 4. The SSEM Replica technical team in 1998. Adrian Cornforth, Suzanne Walker (project photographer), Charlie Portman, George Roylance, Bill Purvis, Chris Burton, Ken Turner, and Keith Wood. (Courtesy the Museum of Science and Industry in Manchester.)

Getting on with the construction

Earlier I described how, at the end of 1995, a team of six volunteer helpers was recruited from among friends and former colleagues. Figure 4 shows the group, together with the team photographer (Suzanne Walker) who had joined later to help record progress. All were motivated by the fascination of reconstructing a piece of history and were proud to use their individual skills to meet the project's objectives. Most had experience working on vacuum tube technology and had appropriate respect for high voltages. By that time, the feasibility rig was beginning to work at my home, and a technical modus operandi had evolved. Each team member was assigned one section of the computer. His task was to take the circuit diagrams and photographs and study them to become thoroughly familiar with how the system worked. He should then be able to deduce the most likely detailed design for his section as it was on 21 June 1948. As project manager, I attempted to maintain consistency and to arbitrate interpretation of the documents. Everybody worked at home in their spare time, some of the team still being in full-time employment. As the familiarization process progressed, increasingly frequent team meetings were held at the University of Manchester to review progress and solve problems.

The circuit diagrams were the basis for a team member's investigation. Each diagram represented the circuit of one chassis in the machine, but initially there was hardly any clue as to which chassis was which as seen in the photographs. The panoramic photograph in *The Illustrated London News* article mentioned earlier did have some annotations as a starting point. By a process of trial and elimination, the team established a plausible overall physical layout, so that a given photograph from one of Alec Robinson's set dating from December 1948, depicting a chassis, could be matched with a given circuit diagram. The photograph was scanned and presented as an image on a PC using Corel's Paint Shop Pro, where it could be examined to try to establish two design requirements by determining how the components were laid out on the chassis, and what the dimensions were for the chassis. Although all the chassis had a general similarity (for example, it was found that usually the vacuum tubes were mounted on 2-inch centers), each one was unique for its function.

The tedious process of establishing the positions of the visible holes was done by measuring, on the scanned photograph, the local pixels per inch using known dimensions such as the standard rack drillings. Once a large number of dimensions were measured, patterns began to emerge. For example, the measuring and scaling process indicated that the flanges on the chassis shelf were typically a half inch wide. The recurrence of this dimension, measured and scaled in several places, gave some confidence in its correctness, and a half inch was assumed in those cases where direct measurement was difficult. Chassis that were more distant in the photographs were much harder to measure, and the emerging patterns were

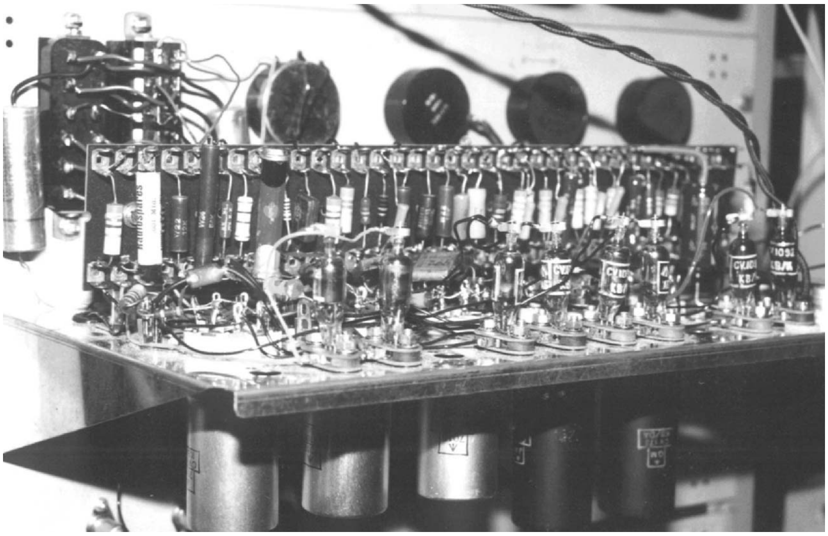

Figure 5. Horizontal time-base chassis in the replica showing vacuum tubes hanging downward and components on tag-boards. Potentiometers and connectors are mounted on the panel. (Photo by Suzanne Walker.)

used to provide plausible dimensions.

As each chassis' dimensions were deduced, a computer-aided design (CAD) drawing was created using Evolution Computing's EasyCad for the pieces of metalwork. These CAD drawings were the first engineering drawings to exist for the part. The drawings of the chassis were then sent to ICL's engineering workshop for fabrication. The original SSEM used stock steel front panels of various heights, obtained from TRE, and the original shelves were made at the university, cut from a large sheet of tinplate. In 1996, we used the same materials although the new panels were individually fabricated. Approximately 60 chassis had to be designed and made. When the metalwork for a chassis was ready, the team member took it home together with the needed components, and assembled and wired it there according to the appropriate circuit diagram. Figure 5 shows an example of one of the chassis, the horizontal time-base generator.

Study of the photographs yielded many other surprisingly useful details. One example is the tuning condenser visible on one of the chassis. The circuit diagram for the basic clock shows a tuned-plate, tuned-grid oscillator using such a capacitor, which provided a positive identification of the chassis in the photograph. On the nearer chassis in the photographs, it is even possible to identify some of the connecting wires, and this allowed us to reproduce these interconnections in the replica.

An interesting discovery was the way the typewriter push buttons were wired. The illustrations show that the buttons are arranged in an array of eight columns and five rows. The SSEM used a 32-bit word, so only 32 of the 40 buttons were used, the remainder presumably being a contingency in case the SSEM developers wanted to experiment with longer word lengths (which is easy in a serial computer). We had naturally assumed that the assignment of buttons to bits in the word was left to right, then top down, and had wired them in this sequence. However, a piece of BBC newsreel film has survived from 1949, showing about 90 seconds of views of the SSEM/Mark 1. One clip is of Tom Kilburn inserting bits into the memory, and it is clear that he is moving his hand down the columns rather than across the rows. Of such trivia is authenticity attained. Strangely, a few weeks after that discovery, another photograph was found in the university archives, which, when sufficiently enlarged, revealed that each push button had its bit number painted on it. The figures are very faint but confirm the columnwise wiring.

Throughout the project so far, I had attempted to keep a photographic and video record of our activities, but the time needed to do this, and the burden of trying to remember to do it, was becoming onerous. We needed a "project remembrancer," and so I approached my cousin Suzanne, a former teacher of mathematics and an enthusiastic photographer who was working toward her audiovisual associateship of the Royal Photographic Society, and asked if she would like to join in. She was able to join our Tuesday sessions at the university to contribute a comprehensive pictorial record of the reconstruction activities, resulting in about 700 photographs and more than 10 hours of camcorder footage.

Testing and commissioning

As mentioned earlier, the University of Manchester had offered a site to build the replica in the big Computer Hall, and the project would rub shoulders with the huge Cray and ICL service mainframes and disk farms. One whole wall of the hall is plate glass alongside a major internal walkway, and our work took place in good view of passersby. This provided good publicity during construction and enabled anybody to see what was happening even when members of the project team were not present.

Mixing Old and New Computer Technology

Electronics engineers today have access to vastly more powerful and versatile test and measurement equipment than did the pioneers in the 1940s. Most of this improvement has come about through exactly the same advances in electronic technology as have driven the improvement in computers. We took advantage of the new technology to assist in commissioning the Small-Scale Experimental Machine (SSEM) replica, and two examples are described here, the dummy stores and the interfaced personal computer. Two other examples are not described: the PC-controlled switch array that can operate all the SSEM control switches under program control, a technique that has not yet been fully exploited; and a real-time signal comparator, which lights indicator warning lamps should the contents of a CRT memory differ from the corresponding dummy store.

Dummy stores

As mentioned in the main text, dummy stores were developed that could be switched in, in place of the CRT storage subsystems. The dummy stores were built so that the main system could be commissioned independently of the CRT memories.

Consider a cathode ray tube storing a line of 32 digits according to the principle explained in this article's "The Principle of CRT Storage" sidebar. The beam is made to sweep repetitively across the tube so that the bits can be read out and refreshed if necessary. Each time the beam sweeps across, 32 narrow (2-microsecond) pulses 10 microseconds apart drive the grid of the CRT. These grid pulses turn on the beam so that if a 1 was stored at the corresponding spot on the screen, a 30-volt positive pulse is generated by the pickup mesh and amplifier, or else a 0-volt pulse for a 0. If this output pulse is positive, then the external circuits instantly cause the corresponding grid pulse to change from narrow to broad (6 microseconds wide).

It is easy to replicate the grid pulses and the amplifier output pulses using standard integrated circuits. For one 32-bit word, a single 32-bit shift register is all that is needed, clocked by the 32 grid pulses. The shift register can be made to store a 0 or a 1 at each clock pulse depending on whether the grid pulse is narrow or broad. The 32 bits thus stored in the shift register will emerge in the following cycle when the next set of grid clock pulses are applied. These emerging pulses correspond exactly to the output signal from the CRT mesh and amplifier. The shift register circuit just described can therefore be directly substituted for the CRT, pickup mesh, and amplifier in the main system.

This simple dummy store with one shift register is suitable for the accumulator (see this article's "Functional Structure of the Baby" sidebar) which has just one line of 32 bits. The control CRT has two vertically adjacent lines, so its dummy store has two shift registers, either of which is selected by the same signal that provides the vertical deflection of the trace on the CRT. The main CRT memory has 32 adjacent 32-bit lines, any one of which can be selected by the 5-bit word address. Rather than provide 32 shift registers for this dummy store, we used a simple circuit using a small static random access memory (SRAM) and a few complementary metal-oxide semiconductor (CMOS) ICs.

Each dummy store is built into a small metal box a few inches across. The dummy stores are constantly operational, and a simple manual changeover switch selects the

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The power supply system, the racks, and the feasibility rig were installed in the Computer Hall in early 1996. As team members finished a chassis, they brought it to the university, usually on a Tuesday Team Day, and added it to the growing replica. Chassis were interconnected by wiring between the terminals on the panels. In the early stages, the feasibility rig could be used as a source of signals so that a chassis could be partially tested. The pattern of the team's working together on the machine one day a week was successful, giving a weekly target for the many offline activities as well as affording people time to attend to the rest of their lives.

The most critical items in the whole machine were of course the three CRT memories. The feasibility rig had given us confidence, but to paraphrase Kilburn's words during one of our conversations, What about the hurly-burly of the replica? Our most experienced engineer in the team, Charlie Portman, took on the task of achieving working memories. A couple of special chassis were made so that the memories could be interfaced to the printer port of a PC (see the "Mixing Old and New Computer Technology" sidebar). A series of special programs were written to run on the PC in order to exercise and diagnose the memory operation. At this stage it was a great joy to have Kilburn and Edwards come in and sit with us in front of the CRT boxes, helping to get those to work just as they must have done 50 years before. It was chastening to realize that they had achieved the task then without the benefit of our modern test equipment, and especially without the benefit of a personal computer.

Although the description of the CRT memory operation given elsewhere seems straightforward, as an analog electronic device it was tricky to adjust. Controls for brilliance, focus, astigmatism, high-voltage supply, deflection voltages, amplifier gain, threshold level, dash width, dot width, and strobe pulse timing all interacted. The secondary emission behavior

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output signal either from the CRT or from the dummy store to pass on to the subsequent clocking and gating circuits. The dummy stores have proved valuable in emergencies when the machine has to be demonstrated yet one of the CRTs might need maintenance.

PC interface

A personal computer interface to the Baby lets a PC exercise the CRT memory and conveniently load programs from a library directly into the CRT memory for running. The implementation of the interface exploits two features of the Baby design:

- Many signals in the Baby are negative-going pulses of, say, 10 volts, which typically fully switch the grid of one of the VR91 pentodes. Such a signal can be easily generated using a standard RS-232C line driver IC type 75188 or similar, in turn driven from the parallel port of the PC. Similarly, a simple resistive level-translator and CMOS buffer can convert such signals so they can be fed into the parallel port.
- The 10-microsecond clock period of the Baby is slow enough that a 1990s PC (with an Intel 386 CPU) can execute a small instruction loop within one clock period.

A special small interface chassis was built to fit into the replica and which performed the voltage level conversions for the basic clock, for a signal representing the start of the scan of the 32 lines on the main CRT, for the data-out signal from the CRT, for the data-in signal to the CRT, and a signal to erase a word in the CRT. Only three small integrated circuits are required. The chassis can just be seen in Figure 6 (in the main text) in the second rack from the right, level with the bottom of the monitor CRT; it has a cable that plugs into the parallel port of the PC. Note that there is no intervention into the Baby's logic other than one additional diode to enable data to be input. All the other interface signals are analogous to attaching an oscilloscope probe to a terminal.

The author wrote a series of programs in Turbo Pascal to run under MS DOS on the old 386 PC, which had been donated by the university. These all depend on assembly subroutines containing instruction loops that poll the level of the three input signals. It was easy to monitor the start of the CRT scan, transfer to a loop monitoring the edge of the clock pulses, and read the state of the data-in wire, or write to the data-out wire. All timing is done by counting clock pulses in the program. Reading from and writing to the CRT takes place in the scan phases of CRT operation and is invisible to the action phases of the Baby.

Sophisticated test programs were written to thoroughly exercise the CRT store. One utility program lets us access a database of Baby programs (each is of course just a sequence of 1,024 bits), and instantly load a chosen program into the CRT. This saves the tedious and error-prone manual insertion of programs bit-by-bit via the switches and push buttons. A spare switch on the Baby informs (via the interface chassis) the PC to perform the load operation.

Interfacing a PC has been relatively simple, and it is satisfying to think that the PC is helping to resurrect its ancestor. As mentioned earlier, there is also a PC-controlled chassis able to operate all the switches and push buttons, and so it is technically feasible eventually to operate the Baby replica entirely remotely, for example over the Internet. Perhaps another generation of enthusiasts will have the time to plan and write the appropriate software.

of the screen phosphor is not uniform in the early tubes used in both the SSEM in 1948 and in the replica, and furthermore they are susceptible to minute areas of zero emissivity, known as phoneys, where a bit cannot be stored. (*Phoney* is a sort of slang word used by World War II pilots meaning a radar echo that was not a real target. The term carried over to the SSEM team in 1948.) By 1949, the original tubes had been replaced by tubes manufactured in especially clean conditions to eliminate those problems.

The team made an early decision to separate the work on the CRTs from the rest of the machine, and to run the two activities in parallel. To enable the main machine to progress, *dummy stores* (that is, working memories that functionally took the place of the CRT storage subsystem) were built, using semiconductor components, so that the whole machine could be made to work without CRTs (see the "Mixing Old and New Computer Technology" sidebar). These dummy stores have proved to be extremely useful and remain in the replica—in small boxes that hang in the back wiring—to be switched in to help with fault diagnosis and isolation.

By summer 1997, the whole machine was beginning to work, and attempts were made to run programs. One team member, Keith Wood, had written a program that moved a pattern across the store, viewable on the monitor CRT. This stunning program, which we believe had not been attempted in the original machine, vividly shows a modern audience that this really is a universal computing machine. The structure of the program was so different from any program we know about from 1948, all of which solved arithmetical problems, that it seemed to nicely illustrate Turing's perception of a universal symbol-manipulating machine.

As part of the lead-up to the 50th anniversary celebrations, the university organized a worldwide competition to see who could write the "best" program for the SSEM, with suitable prizes to be awarded. To support the competition, a programming manual was written, along with a simple simulator for entrants to use to test their entry prior to submission.[14] Nearly 130 entries were received from about 20 countries. Almost all the entries worked on the replica, and many exploited the graphical nature of the monitor CRT to show some sort of moving graphic. The winning entrant was a student from Japan, who personally ran his program on the replica during the afternoon of 21 June 1998.

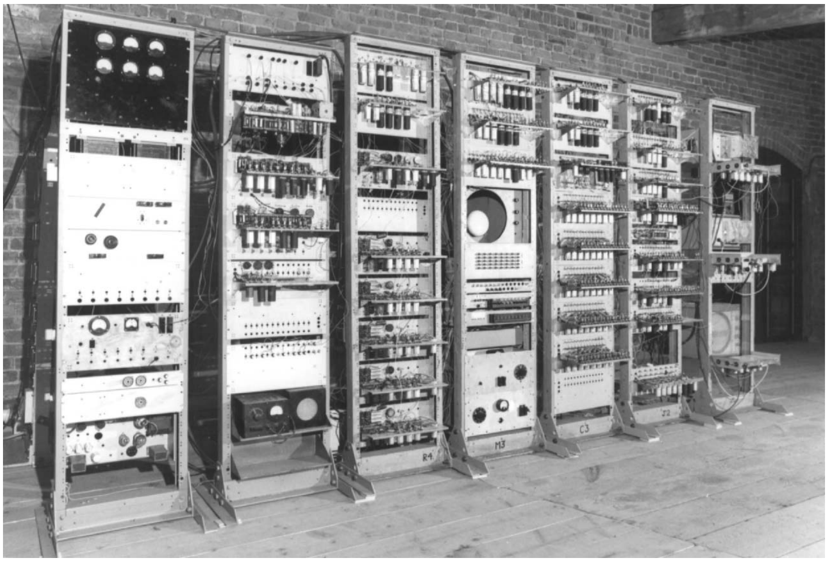

Figure 6. The Replica SSEM after delivery to the Museum of Science and Industry in Manchester in February 1998. Replacement of all the interconnections had not yet started. (Courtesy of the Museum of Science and Industry in Manchester.)

Over the winter of 1997–1998, several months were occupied with just running the computer and making observations and adjustments to improve the reliability. The feasibility rig, no longer needed as a source of signals, could be removed from the scene. The PC interface was tidied up and adapted so that we could instantly load a program into the SSEM memory from a database of programs in the PC without having to always go through the slow and error-prone procedure of entering individual digits from the switches and push buttons.

Preparations were made to move the machine to the MSIM, where it would be put on display and where the anniversary celebration would take place. The machine was to be installed in the 1830 Warehouse, the world's first railway goods warehouse and actually built in 1830. The brick walls and wooden board floors were reminiscent of the old Magnetism Room and so entirely suitable to house the replica (see Figure 6). The transportation plan was to separate the system into individual racks by labeling and disconnecting one end of each interconnecting wire. The racks would then be moved using an air-cushion vehicle for transport. It was chastening to see the machine completely dismantled at the university ready for moving, and with only four months to go to achieve our goal.

Relocation

Estimates as to how long it would take to get the machine working again after moving the few miles from the university to the museum ranged from two weeks to two months. February 1998 was chosen to allow enough time to be on target for June. The team had done such a good job of labeling and preparation, and the moving gang from ICL was so careful, that the replica was running programs again two days after arrival at the museum. This was a great tribute to the care and commitment of the team and the movers, and having a working machine so quickly gave us plenty of time to get used to using the machine in the new environment. During this period another chassis was added out of sight at the rear of the machine, containing a set of relays whose contacts are in parallel with the SSEM control switches and push buttons. The relays are controlled via an RS-232 interface from a PC, with the intention that one day it may be possible to connect the replica to the Internet to allow remote operation of the machine.

Jubilee celebrations

During the week before 21 June 1998, among many other celebratory events, a formal switch-on of the replica by Kilburn and Lady Williams, Freddie Williams's widow, was staged using a satellite link from the 2,000-seat Bridgewater Hall auditorium in Manchester City Center. Over the next day or two, one of the storage systems became unreliable, and we had to revert to the dummy store for that particular CRT. On Sunday, 21 June 1998, at 11:15 a.m., Kilburn and Tootill ran the first program again, just as they had done exactly half a century earlier. Their evident pleasure in that

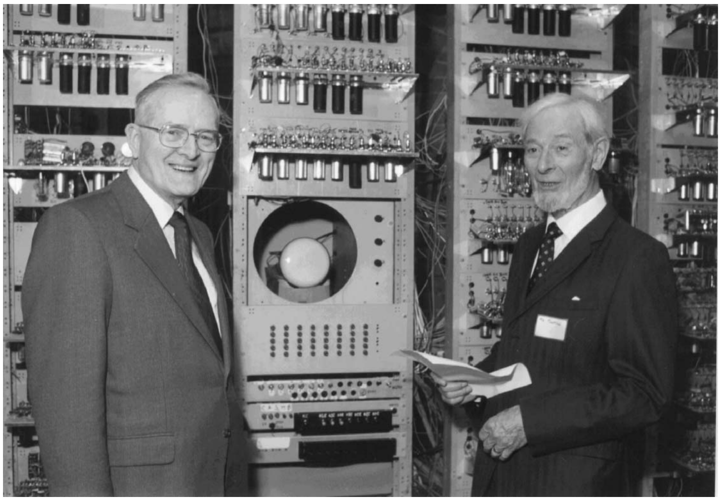

Figure 7. Tom Kilburn and Geoff Tootill after running the first program on 21 June 1998. (Courtesy of the School of Computer Science, the University of Manchester.)

moment was captured in a photograph taken immediately after (see Figure 7).

Ongoing commitments

Since that date, the replica has fulfilled the project objectives by being on public display in the museum, with live demonstrations on Tuesdays and many school holiday weekends. A team of demonstrators has been trained to switch the machine on, run programs on it, and in particular to explain to the public the historical significance of the original SSEM. Efforts are being made to train some of them to be able to repair the machine in the future.

What we learned from this project

Building the replica and running the first program on 21 June 1998 certainly achieved the project objectives, but it is also interesting to speculate on what else has emerged, particularly from a historical point of view. At the time of this writing, it is some six years since the 50th anniversary, and this is perhaps too short a time to take a comprehensive view. Nonetheless, there already seem to be several unexpected justifications for the project.

It is probably fair to say that much of what was learned could have been learned anyway by studying the documentation and interviewing the pioneers—essentially, just from thinking hard about the original machine. But building the machine provided a powerful motivation to do that thinking and so can be said to have advanced our knowledge about a short but important period of computer history. The great interest generated by the 50th anniversary, and in particular by the replica, caused historical questions to be asked that probably would not otherwise have been asked.

One of the most useful results was learning details from the pioneers themselves when they were confronted with the machine. Like most people, they found it easier to recognize something than recall it. They willingly offered a great deal of information in preliminary interviews, but this was augmented when they saw the replica. An example was when Edwards was puzzled by the appearance of the Accumulator CRT—"It didn't look right." This prompted him to remember that initially they used a 12-inch, not a 6-inch, tube. Fortunately, we were able to obtain the correct tube and suitable hardware to make the change. Again, when Edwards and Kilburn were helping us get the CRT memories working, they were able to point out details and characteristics that only they could provide, because the way they thought about electronics technology in 1948 was inevitably different from our present-day perceptions. And, of course, the remarkable work that Kilburn and Tootill did in rediscovering the actual coding for the first program only came about because we had set the project goal to run that program. The input of the pioneers undoubtedly lent a reassuring sense of veracity to the replica.

Assessing the documents was an essential part of achieving authenticity. The surviving circuit diagrams and photographs, most of which are undated, had to be correlated to establish a chronology. This result can be regarded as new knowledge and may be of use to future scholars. It could have been done anyway, but the project forced the issue. The many discovered constructional details, such as the type of push buttons, fall into the same category.

New experiences have resulted that would otherwise have been unknown. One of the most interesting is the view of the machine from the panel side. No photographs exist, and it was like seeing the far side of the moon for the first time. Another is the experience of standing near a machine that is dissipating 3.5 kilowatts—it has an authentic smell. I once asked Tootill how they kept the laboratory cool. "Oh, we kept the windows open, even during the winter!" he replied. Kilburn has generously said that the replica is indistinguishable from the original, though Robinson qualified that by saying that it was not dirty enough yet.

The most inauthentic aspect of the replica is its reliability. The pioneer team had warned us of the dire problems we would have in keeping the machine working. In 1948, Williams had instructed that the SSEM was to be kept powered up all the time, especially the heater supplies. Edwards said that Williams insisted that the soldering irons have their earth leads removed so that modifications and repairs could be done with all the power on. (No doubt they drew the line at working on the high-voltage CRTs.) Tootill said that, even so, they typically had to replace one or more vacuum tubes every day, often due to heater-cathode short-circuit in the diodes. The conventional wisdom is that switching on and off does the most harm and that vacuum tubes are most vulnerable when switched on from cold. On the replica, we went to some trouble to provide slow run-up for the heaters using a big Variac variable transformer. Our actual experience has been far more satisfactory than the warnings implied, though admittedly the machine is only run for a few hours every week. Probably no more than 10 or 20 vacuum tubes have been replaced in the past five years, with nearly as many small components. On the other hand, the CRTs have been more troublesome than expected.

Several possible explanations exist for the unexpected reliability of the vacuum tubes and the unreliability of the CRTs. Most of the common VR91 pentodes and VR92 diodes were manufactured in the 1950s or later, a time when vacuum tube manufacturers were striving for high-reliability products, whereas the CRTs were made in the 1940s in wartime conditions. Furthermore, in building the replica, it was possible to build directly to the final design, whereas the original machine would have suffered much modification and change as the original team homed in on a working system. And no doubt modern solder and flux are better than they were 50 years ago.

The project provided a range of satisfactions and rewards. Members of the volunteer team reminiscing on their experiences recorded their motivations and feelings about the project. Some of the shared highlights include

- the challenge of a well-defined, unusual, and important task;
- the pleasure of getting back to the technology of their youth;
- the friendship and happiness from working in a well-motivated team;
- the delight at the success of achievement, both of individual milestones as well as of the final goal; and
- the satisfaction of participating in ceremonies, celebrations, and media exposure.

Conclusions

I offer no excuse for building the replica: Everyone involved agreed that it was a satisfying and challenging experience. Computer history can be studied in many ways, and for engineers the preservation of engineering creations is one way to present evidence for study. We hope that the Baby replica will survive to help later generations of historians to get a feeling for 1940s electronic technology. New historical information has also emerged from the pioneers and from assessing the surviving documents, with the reconstruction providing the stimulus and need for detailed scrutiny of surviving sources.

Acknowledgments

A project such as this could not have been done without the support and encouragement of a great many people. Special gratitude is due to the families and spouses of the participants. Our enthusiasm could only be sustained as a result of the sacrifices and patience of those behind the scenes, stoically deferring to the pressures of the project, and who get little enough recognition for the disruption to their lives. The pioneer team offered many kindnesses. Sadly, Tom Kilburn died in 2001, but it is believed that his participation in the project gave him much pleasure in his retirement. University of Manchester staff willingly provided much help in kind and facilities throughout, and particularly in getting the project off the ground. ICL's generosity in providing sponsorship made the project possible, and ICL continued to offer support after 1998 to make sure that the machine could be maintained. The MSIM provides a suitable home for the replica, which will soon form part of a large and ambitious gallery sequence explaining Manchester's contribution to computing. Finally, the friendly enthusiasm of the Computer Conservation Society, particularly of the project team, ensured our goal's achievement. It was a great sorrow and shock when the team's friend and mentor Charlie Portman died a few months after the June 1998 event. He had patiently persisted with the CRT stores until they worked. I lost a lifetime friend and colleague.

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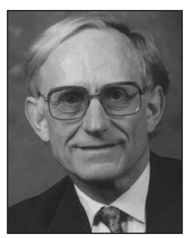

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