ENIAC as a Stored-Program Computer: A New Look at the Old Records

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In this article, I present evidence that ENIAC was converted to operate in stored-program mode in March–April 1948; before the Manchester Baby, albeit of course it was only in the Manchester Baby that it was a read/write memory. In his article marking the 60th anniversary of the ENIAC, "The Second Life of ENIAC" (*IEEE Annals of the History of Computing,* vol. 28, no. 2, 2006), Hans Neukom observed that the ENIAC first operated in stored-program mode in September 1948; a date that, if accurate, gives precedence to the Manchester Baby as the first stored-program computer. Subsequent research, however, has shown that this had already been achieved in March–April 1948.

The principal evidence for this is the letter[1] from John von Neumann to Stanislaw Ulam, dated 11 May 1948 referred to by William Aspray in his book *John von Neumann and the Origin of Modern Computing.*[2] After some reference to family matters, von Neumann wrote:

> Nick [Nick Metropolis] and Klari [von Neumann's wife] finished at Aberdeen. It took 32 days (including Sundays) to put the new control system on the ENIAC, check it and the problems code, and getting the ENIAC into shape. The latter was probably 2/3 of the time. Then the ENIAC ran for 10 days. It was producing 50% of these 10 $\times$ 16 hours, this includes two Sundays and all troubles. It could have probably continued on this basis as long as we wished. If a new problem was put on, the 32 days "break-in" period should contract to 2–6 days. It did 160 cycles ("censures," 100 input cards each) on 7 problems.[3]

The conversion referred to was clearly stored-program mode with the program being stored in the function tables, but using the 60-order code version rather than the final 100-order code version used from later in 1948.[4] This mode made ENIAC much quicker to program but significantly slower in operation.

Nick Metropolis reported more fully on the process of converting ENIAC and what he and Klari were doing.

> On one of his many visits to Los Alamos (circa 1947), von Neumann described a suggestion of Richard Clippinger of the Ballistics Research Laboratory that the ENIAC might be converted into a limited stored-program mode of operation instead of its gigantic plugboard mode distributed over the entire machine. The idea was that the so-called "function tables," normally used to store 300 12-decimal digit numbers set by manual switches, could be used to store up to 1800 2-decimal digits that would be interrogated sequentially (including loops), each pair corresponding to an instruction. Thus one could go from one problem to another much more efficiently.
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> Adele Goldstine at Princeton indeed started to plan the background control to implement this form of control. Halfway through this stage, it was apparent that the control capacity of the ENIAC was insufficient. However, on a visit to the ENIAC in early 1948, in preparation for its use after its move from Philadelphia, I was briefed by Homer Spence, the quiet but effective chief engineer, about some of their plans, He mentioned the construction of a new panel to augment one of the logical operations. It was a one-input-hundred-output matrix. It occurred to me that if this could be used to interpret the instruction pairs in the proposed control mode, then it would release a sufficiently large portion of the available control units to realize the new mode—perhaps. When I mentioned this to von Neumann, he asked whether I would be willing to take over the project, since Adele had lost interest; so with the help of Klari von Neumann, plans were revised and completed and we undertook to implement them on the ENIAC, and in a fortnight this was achieved. Our set of problems—the first Monte Carlo—were run in the new mode. Subsequently, J. Calkin, F. and C. Evans, and J. Suydam were to utilize the ENIAC for an extensive series of problems.[5]

A primary aim of Nick Metropolis (and later of his colleagues, Calkin and Evans, at Los Alamos) was to run an experimental program on the ENIAC in the postwar years to determine the feasibility of Edward Teller's "Super" thermonuclear weapon. At that time, this concept device was controversial because it was neither practical nor was it known if it was even feasible. Consequently, researchers believe that the actual programming material is still classified for good reasons. Accordingly, it is almost certain that relatively little has been known about early work on ENIAC in stored-program mode and particularly about the work done in spring 1948. Of course, the program to be run on the ENIAC in 1948 was only a small part of what was necessary to determine the feasibility of the "Super." No computer at that time was capable of tackling this problem as a whole.[6]

In his article, Metropolis did not give the date of the work, but his later writings and other sources place it in the winter and spring of 1948.[7]

ENIAC and the Manchester Baby

From a historical point of view, there is a crucial difference between ENIAC operating as a stored-program machine in March–May 1948 as against September 1948. This arises because the Manchester Baby, which operated as a stored-program machine from the beginning, is known to have first operated on 21 June 1948,[8]

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and the April–May 1948 date gives ENIAC some claim to priority.

The Manchester Baby was the brainchild of Frederick Williams and Tom Kilburn, aided by Max Newman. As of 21 June 1948, the Manchester Baby had 32 words of storage, each of 32 bits and a very limited instruction set. This 32-word memory had to accommodate both program and data. At that time, the Baby had no mechanical form of I/O such as paper tape or punched cards. The machine's logic was essentially simple and used the von Neumann architecture.[9]

In its original mode of operation, ENIAC was extremely complex. The machine used parallel programming and operated in decimal. Programming took place by physically changing the plugging system. Accordingly, although the machine was reasonably fast, the process of programming a new problem could take many days, leaving aside the difficulties of testing a new program. ENIAC's storage consisted of 20 accumulators (all read/write), the constant transmitter containing 10 further immediate access memories (read only) of which 8 could be changed by reading a card while the other two were set up on hand switches, and three function tables (read only, each containing 104 memories), set up on hand switches. All were random access and most could be used to accommodate two 5-digit or one 10-digit decimal numbers. ENIAC had excellent I/O facilities using punched cards.[10]

Various individuals claim to have been the first to realize that ENIAC could be converted to operate as a stored-program machine without the constant re-plugging of units but sacrificing its parallel operation. Mauchly and Eckert have said that they had this in mind from the outset.[11] Von Neumann certainly suggested it later.[12] Beginning in spring 1947, several people started to try out this new mode of operation, including Goldstine's wife. Later ENIAC was moved to the Army Ordnance proving ground at Aberdeen, Maryland, where it came under the control of Richard Clippinger, who was also keen to try out ENIAC in a stored-program mode.

ENIAC's work in spring 1947

Even those who worked close to ENIAC have asserted that, in its new mode, ENIAC's instructions were stored in the function table and consequently could not be changed at runtime. ENIAC could therefore not modify its own program. However, this statement is somewhat misleading on two counts: First, instructions could also be read from the constant transmitter and hence input by reading a card. It appears, however, that this facility was not incorporated in the 60-instruction set and probably not available until later in 1948. Second, the program normally operated by sequential instructions. The jump instruction, whether conditional or unconditional, operated by taking the next instruction from an address stored in an accumulator. But the contents of this accumulator could, of course, be computed by the machine. Accordingly, ENIAC could alter the course of a program at runtime, and indeed Metropolis and Klari von Neumann used this feature in spring 1948. A manuscript that Klari wrote, headed "III Actual Technique—the Use of the Eniac,"[13]—written by Klari with some amendments added in a different hand, most likely that of John von Neumann—stated:

> Before describing the details of the actual running of the six [the word "six" has a soft line through it and the word "first" is put in faintly above, seemingly by von Neumann] experimental problems based on the Monte Carlo method, we would like to discuss here briefly the new and seemingly more efficient method of operation which was used for the first time on the Eniac.[14]

This work is also described in Ulam's autobiography:

> At each stage of the process, there are many possibilities determining the fate of the neutron. It can scatter at one angle, change its velocity, be absorbed, or produce more neutrons by a fission of the target nucleus, and so on. The elementary probabilities for each of these possibilities are individually known, to some extent, from the knowledge of the cross sections. But the problem is to know what a succession and branching of perhaps hundreds of thousands or millions will do. One can write differential equations or integral differential equations for the "expected values," but to solve them or even to get an approximative idea of the properties of the solution, is an entirely different matter.
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> The idea was to try out thousands of such possibilities and, at each stage, to select by chance, by means of a "random number" with suitable probability, the fate or kind of event, to follow it in a line, so to speak, instead of considering all branches. After examining the possible histories of only a few thousand, one will have a good sample and an approximate answer to the problem. All one needed was to have the means of producing such sample histories. It so happened that computing

> machines were coming into existence, and here was something suitable for machine calculation.[15]

Unfortunately, Ulam's autobiography did not mention the ENIAC work, yet he originated the idea behind the program. Von Neumann then worked on the detail. Von Neumann's 11 March 1947 letter to Robert Richtmyer provided a full description and attached a "Tentative Computing Sheet" setting it out. The sheet contains about 130 lines, most of which would require at least two instructions: "I cannot assert this with certainty yet, but it seems to me very likely that the instructions given on this "computing sheet" do not exceed the "logical" capacity of the ENIAC."[16]

By December 1947, the situation had evolved: the Herman H. Goldstine Collection at Hampshire College contains a detailed flowchart, including allocation of accumulators, for what is essentially the same problem, dated 1 December 1947.[17] The author is not attributed but, on the basis of the handwriting, perhaps Adele Goldstine is more likely than Klari von Neumann.[18]

The actual procedures used in the program are best seen in Klari von Neumann's manuscript "III Actual Technique—The Use of the ENIAC" earlier referred to:

> Next we examined wheather [sic], for the particle travelling with the known velocity at the distance d_1, there was still time left within the census interval for the collision to occur. If T was reached, d_e was formed at the point where the neutron arrived at census time, $d_2 = (T-t)\ v$, and the event was noted as census. t_1, the time of the event occurring was then put equal to census time T. If however t did not exceed T, the new t was formed by adding the distance over velocity to the previous t; $t^* = t + d_2/v$, where $d_1 = d_2$.[19]

The difficulties of keeping sufficient significant figures in the calculation is illustrated by another paragraph:

> For certain considerations of storage space on the numeric Function Table and in order to be able to carry sufficient significant figures, scaled numbers, S_J for the individual and Sigma for the total cross-sections were used here instead of the true cross-section value. The scaling factors and the system of using them will be described in a separate section of this report.[20]

Because 100 neutrons were considered in one time interval, it was necessary to punch out intermediate states of the system and read them in later. The modeling required a long random-number series.[21] The first of the series was input as an eight digit number. This was then squared and the middle eight digits used as the new random number (the so-called von Neumann middle square digits).[22]

Thus even in spring 1948, ENIAC's users engaged its ability to modify its programs at runtime, which was almost certainly the first use of a subroutine in a stored-program electronic computer. This capability of ENIAC is confirmed by Barkley Fritz: "Certain of the 20 memory registers (several of the accumulators of the original ENIAC) were allocated for program modification and provided ENIAC its stored-program capability in 1948."[23]

How the claims compare

Compared to the Manchester Baby, the ENIAC was much more powerful, capable of operating far more complex programs. But on the theoretical side there was one difference of substance. The Manchester Baby could change the course of the program during runtime by means of computations made both by changing the program to use a different set of instructions and by changing the instructions themselves. ENIAC could, and did, perform the first of these but not the second.[24]

From a practical standpoint, the ability to modify instructions at runtime is a significant advantage and can save a great many instructions from being stored. It is necessary from a theoretical standpoint to ensure that a computer can solve the whole range of possible problems.[25] Here it is interesting to note the claim made by Williams and Kilburn for the Manchester Baby in their first announcement of it. They wrote:

> … the programme [sic] can be changed without any mechanical or electro-mechanical circuit changes.[26]

On that criterion alone the Manchester Baby was not clearly superior to the ENIAC. However Williams and Kilburn were undoubtedly unaware that the ENIAC had been converted prior to 21st June 1948. The Manchester Baby was designed very much as a general-purpose computer but because of its small store its actual possibilities were extremely limited. The ENIAC was designed specifically for ordnance calculations, but experience showed that it could undertake a wide range of scientific work.

In his comments to Arthur Burks and Alice Burks on their paper regarding the ENIAC, Brian Randell argued that the ENIAC in non-stored-program mode was a not a general-purpose computer. His argument:

> More seriously, surely any computer that we would now regard as having "general-purpose programming ability" has, as a crucial feature, the ability to select among items held in its read-write memory based on results so far computed.[27]

But at least in stored-program mode the ENIAC could do this because it could perform an unconditional jump to one of a series of orders, each of which addressed a different memory location. This selection of the "jump to" instruction was determined by a number stored in an accumulator which could be based on results so far computed. The extent of the read-write memory was small, but in principle the ENIAC in stored-program mode could be said to have "general-purpose programming ability" in the terms set by Randell.

Perhaps it is because Goldstine wrote that ENIAC was converted to stored-program operation only in September 1948[28] that ENIAC's claim to a significant priority has been obscured in at least one respect. Only the letter from von Neumann to Ulam, supported by the manuscript report of the work done in March−May 1948 and by Metropolis's two writings, make clear what ENIAC had achieved prior to the first operation of the Manchester Baby.

Concerning program modification at runtime, even those who worked with ENIAC sometimes gave an incorrect impression. Harry Read, who worked on ENIAC at the Ballistic Research Laboratories, and Harry Huskey, who worked on the machine at the University of Pennsylvania, both referred at a 1996 symposium to the conversion of the ENIAC in the following terms: "So you almost had a stored-program machine, but you couldn't modify the program when you were running. The switches were set and that was it."[29]

It seems reasonable to argue that the Manchester Baby's achievement is wrongly singled out as the clear first in the stored-program stakes.[30] Equally it would be wrong for ENIAC to steal that whole prize. As for the program run on the ENIAC in spring 1948, this has two further firsts to record. It was apparently the first program written for and actually run on a stored-program electronic digital computer. It was also the first program to undertake a simulation: a partly deterministic calculation but which also involves selecting one or more of the variables on the basis of some probability distribution. This process is then repeated many times to provide the overall solution required. Computer simulation has subsequently been used extensively in many fields.[31]

Influence in stored-program mode

Goldstine and von Neumann wrote the first report, circulated widely in the US and Europe,[32] on methods of flowcharting and programming problems for a stored-program computer in 1947 and 1948.[33] Sixteen other machines were built on the same general design, including the commercial IBM 701, for which von Neumann himself wrote programs for solving Schrödinger's equation and testing five-layer meteorological models. So, starting 15 months before the EDSAC, the ENIAC performed a role somewhat similar to, but perhaps even more influential than, the EDSAC, particularly because the US Army agreed to allow university scientists to use the ENIAC free of charge.[34] This makes the first stored program run on ENIAC even more important in the history of computing.

In 2007—the 50th anniversary of von Neumann's death—it is appropriate to reflect that it was he and Klari who both designed and ran this first program. Klari's contribution is all the greater because her formal education ended with high school (Marina von Neumann Whitman, private communication, 5 Feb. 2007). It is also remarkable, because they were first efforts using a new technique, that the ENIAC (like the Colossus) undertook work of significant national-defense importance.

Acknowledgments

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References and notes

1. John von Neumann to Stanislaw Ulam, 11 May 1948, box 5, folder 5, Charles Babbage Inst. (CBI), Univ. of Minnesota, Minneapolis, Honeywell Inc., Honeywell vs Sperry Rand Records (CBI 1).
2. W. Aspray, *John von Neumann and the Origins of Modern Computing*, MIT Press,1992, p. 330.
3. von Neumann to Ulam, 11 May 1948, CBI.
4. R.F. Clippinger, Ballistic Research Laboratories Technical Note No. 673. There were a total of 67 orders: 53 were always used together with one of the two alternative sets of 7. It seems that the two alternative sets were referred to as "Princeton"

and ''Aberdeen,'' presumably reflecting the originators. These orders were first set down by Clippinger as of 13 Nov. 1947.

5. N. Metropolis, ''The MANIAC,'' *A History of Computing in the Twentieth Century*, N. Metropolis, J. Howlet, and G.-C. Rota, eds., Academic Press, 1980, pp. 459-460.
6. Anne Fitzpatrick, private communication, 11 Aug. 2007. Fitzpatrick worked at Los Alamos and knew Nick Metropolis during the latter part of his life. Her research on this topic was published as a doctoral dissertation, ''Igniting the Light Elements: the Los Alamos Thermonuclear Weapon Project, 1942–1952,'' LA-13577-T, Los Alamos National Laboratory, 1999.
7. N. Metropolis and J. Worlton, ''A Trilogy of Errors in the History of Computing,'' *IEEE Annals of the History of Computing*, vol. 2, no. 1, 1980; N. Metropolis, ''The Beginning of the Monte Carlo Method,'' *Los Alamos Science,* special issue, 1987, p. 128; B. Fritz, Ballistic Research Laboratory Memorandum Report Number 617, ''A Survey of ENIAC Operations and Problems 1946-52,'' Aug. 1952, p. 5.
8. S. Lavington, *Early British Computers*, Manchester Univ. Press, 1980, p. 36. The program was a factoring one and ran for 52 minutes on the morning of 21 June 1948.
9. S.H. Lavington, the British Computer Society, *A History of Manchester Computers,* 2nd ed., 1998, pp. 12-17.
10. J.W. Mauchly, ''The ENIAC,'' *A History of Computing in the Twentieth Century*, N. Metropolis, J. Howlet, and G.-C. Rota, eds., pp. 546-547.
11. J. Presper Eckert, ''ENIAC'' *A History of Computing in the Twentieth Century*, N. Metropolis, J. Howlet, and G.-C. Rota, eds., p. 529. Eckert writes ''a possibly long-term setting of the function table switches might be given a permanent set of arguments … Then every time a new set of numbers was read from the card input, a new set of operations would be caused to occur. The foregoing ideas could be easily implemented on the ENIAC, and we expected that at sometime someone would want to do this, so we built the necessary cable to connect 'program pulses' into the function tables in place of 'digit pulses' …''.
12. Aspray, *John von Neumann and the Origins of Modern Computing*, p. 238.
13. Library of Congress, Washington, D.C., Manuscript Division, John von Neumann Papers, container 12, ''Actual Technique—The Use of the ENIAC,'' unpublished, n.d., anonymous report. On page 4 a circled note in different handwriting states, ''Note to Klari: must distinguish between q and q*.'' The handwriting closely reflects that of John von Neumann.
14. Ibid., p. 1.
15. S.M. Ulam, *Adventures of a Mathematician*, Charles Scribner's Sons,1983, pp. 197-198.
16. C.C. Hurd, ''A Note on Early Monte Carlo Computations and Scientific Meetings,'' *Annals of the History of Computing,* vol. 7, April 1985, p. 152.
17. H.H. Goldstine, The Herman H. Goldstine Collection, 1941–1971. Archives, Hampshire College, Amherst, Mass., box 2, Layouts-U, Monte Carlo Flow Diagram.
18. It is not von Neumann himself since he uses quite a different style for ''q.'' See Ref. 15. Further work is desirable both on the handwriting of the December 1947 flowchart (which contains some 80 boxes, many of which would require a considerable number of instructions), comparing it to that of Adele, and also a detailed comparison of the problem contained in the 11 March and 1 December documents and the spring 1948 manuscript. However, for the purpose of this note, only some very brief points from the spring 1948 outline can be included. If this is not widely known, it is perhaps because it was not declassified until 6 July 1959, by which time interest in the ENIAC had largely waned; C.C. Hurd, ''A Note on Early Monte Carlo Computations and Scientific Meetings,'' *Annals of the History of Computing,* vol. 7, April 1985, p. 148.
19. Library of Congress, ''Actual Technique—The Use of the ENIAC,'' p. 9, middle section of page.
20. Ibid., p. 8.
21. Ulam, *Adventures of a Mathematician*, p. 200. Ulam states: ''The first questions concerned the production of the random or pseudo-random numbers. Tricks were quickly devised to produce them internally in the machine itself without relying on any outside physical mechanism. (Clicks from a radioactive source or from cosmic rays would have been very good but too slow.)''
22. Library of Congress, ''Actual Technique—The Use of the ENIAC,'' p. 15.
23. B. Fritz, ''ENIAC—A Problem Solver,'' *IEEE Annals of the History of Computing*, vol. 16, no. 1, 1994, p. 33.
24. ENIAC could have done this if it had the ability to take an instruction from a function table into an accumulator (which it could do) and send that instruction to the master programmer. Almost certainly this could have been arranged, but apparently was not the case. The Manchester Baby did not use this facility in its 21 June 1948 program.
25. The proof that actual modification of instructions is required for all possible problems is contained in C.C. Elgot and A. Robinson, ''Random-Access Stored-Program Machines, An Approach to

Programming Languages,'' *J. ACM*, vol. 11, no. 4, 1964, p. 397.
26. F.C. Williams and T. Kilburn, ''Electronic Digital Computers,'' *The Origins of Digital Computers*, B. Randell, ed., Springer-Verlag, 1982, p. 415.
27. B. Randell, ''Commentary (with Replies by the Authors)'' on A.W. Burks and A.R. Burks' ''First General-Purpose Electronic Computer,'' *Annals of the History of Computing*, vol. 3, no. 4, 1981, p. 396.
28. H.H. Goldstine, *The Computer from Pascal to von Neumann*, Princeton Univ. Press, 1993, p. 233. The specific date of 16 September 1948 is given.
29. T.J. Bergin, ed., *50 years of Army Computing from ENIAC to MSRC*, Army Research Lab, Aberdeen Proving Ground, Md., 2000, p. 30.
30. *Larousse Dictionary of Scientists*, Larousse, 1994, p. 552. Entry for Williams, Sir Frederic Calland. This is a typical reference. The wording here is ''the aptly named Williams Tube became the basis for a prototype machine, built by Williams and Kilburn and which ran the world's first stored-program on 21 June 1948.''
31. Simulation is used in many disciplines other than physics, including in such areas as management science, engineering and epidemiology, as well as in mathematics itself. A recent article (M. Berzins, ''On the Role and Place of Computation in Science and Engineering,'' *Computing in Science and Eng.*, vol. 9, no. 1, Jan./Feb. 2007, p. 98) quotes a US National Science Federation report, ''Simulation also provides a unique alternative to experimental science and engineering, for it can be used to study events not observable or for which measurements are impractical or too expensive,'' as well as showing the complexity of some simulations undertaken today, which can require many hours of computer time. It would be interesting to compare in detail the problem as set out in von Neumann's letter of March 1947, the flowchart of December 1947 and Klari von Neumann's later outline of the work done. If the actual code used could be discovered, this would greatly add to knowledge of this pioneering program. Again, if it still exists, it is probably in one of the closed archives at Los Alamos. Unfortunately, at this time they are completely off limits to the public.
32. Aspray, *John von Neumann and the Origins of Modern Computing*, p. 69.
33. H.H. Goldstine and J. von Neumann, *Planning and Coding of Problems for an Electronic Computing Instrument*, Inst. For Advanced Study, Princeton, N.J., three vols: 1 Apr. 1947, 15 Apr. 1948, and 16 Aug. 1948.
34. Fritz, ''ENIAC—A Problem Solver,'' p. 39.

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