The Circulation of Knowledge and the Origins of the ENIAC:
(Or, What Was and Was Not Innovative About the American Wartime Project)

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Abstract

In presenting this paper at Bletchley Park, there is a unique opportunity to provide an assessment of the extent and limits of the electronic innovations associated with the ENIAC project (Project PX) at the University of Pennsylvania. While it is well known that John Mauchly, J. Presper Eckert and other ENIAC project engineers made several basic contributions to electronic computing, this history has been grossly simplified in broad-level historical accounts. Getting a device with over 17,000 vacuum tubes to operate in an unfamiliar digital domain required a wide array of innovations. By looking at the diverse forms of knowledge embedded in the scientific and engineering practices of those who found themselves at the Moore School, it is possible to document more fully the synthesis of ideas that was coterminous with the invention of the ENIAC. Simultaneously, in documenting the point of origin of the specific bodies of knowledge that comprised the ENIAC, including knowledge embedded in artifacts (e.g. vacuum tubes, switching cables) and skilled practices, it will become possible to document what was innovative and what was conservative about the machine's design. At a theoretical level, this paper also builds on the notion of the "circulation of knowledge." While this concept has recently gained ascendancy within science studies circles, the idea that knowledge circulates through artifacts, engineering techniques and practices should prove to be as valuable for the study of technological innovation and the history of electronic engineering and technology.

In presenting this paper at Bletchley Park, and its work on the Colossus, there is a unique opportunity to assess the extent and limits of the electronic innovations associated with work on the Electronic Numerical Integrator And Computer (ENIAC, or wartime designation of Project PX) at the University of Pennsylvania. While it is well known that John Mauchly, J. Presper Eckert and other project engineers made several basic contributions to electronic computing, this history has been grossly simplified in broad-level historical accounts. Getting a device with over 17,000 vacuum tubes to operate in an unfamiliar digital domain, at a time when electronic devices had at most several hundred vacuum tubes, presented a formidable challenge. It required a wide array of innovations in areas ranging from mechanical design, performance, and testing, to project organization. By the same token, the electrical and radio engineers associated with the ENIAC worked within disciplinary traditions. They would leave open the space for others, such as George Stibitz, John von Neumann, and (Sir) Maurice Wilkes, to work out other aspects of early, computer systems design that lay outside of their disciplinary expertise.

(click to enlarge)

Figure 1. The ENIAC (Source: US Army Photo)[1]

I have two caveats to offer before proceeding with this talk. First, I need to state up front that I have no extensive background in electronics engineering. I do have an electrical engineering and computer science degree from MIT, but as most of you will know, software, not hardware, has driven undergraduate enrollments in such departments since the early 1980s. What I offer therefore are tentative observations based on an untrained eye; I would welcome anyone who might be interested in analyzing the material I present here in greater depth. Second, because of the time available for this talk, I will focus on just three topics.

The first topic has to do with the development of the ENIAC's electronic ring counters. As many of you will know, the ENIAC was not a stored-program computer in the modern sense. It was transitional device that was based on stringing together twenty electronic accumulators along with a number of other specialized units. The ring counters were quite central to the ENIAC's operation. They were analogous to the mechanical counters used in common calculating machines, which in turn were being used by human computers at the Moore School to compute exterior ballistics trajectories.

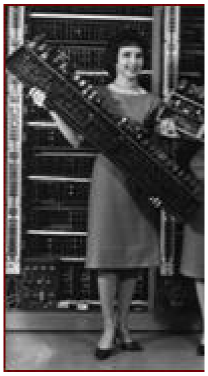

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Figure 2. The ENIAC decade ring counters (Source: US Army Photo)

Designing a reliable ring counter proved to be a formidable challenge for Pres Eckert and his team. Electronic scaling circuits and scintillation counters were already becoming commonplace in particle physics research; local knowledge about such devices was available at the Franklin Institute in Philadelphia. However, these devices had a propensity both to miss a count and to double count, depending on the properties of the incoming signal. This presented no serious problems for most work in particle physics, which relied on statistical analyses. However, by contrast, the numerical methods of integration used to compute ballistic trajectories was not so forgiving, for the algorithm was sensitive to cumulative errors; the fact that an error could occur in any digit could also throw off a calculation in unpredictable ways.

Even before the official start of the project, Pres Eckert had built two “positive action ring counters” in an attempt to address some of the known limitations of these and other devices. However, available knowledge within the Moore School was such that their ring counters could not be made to operate much above 30 to 40 kHz.[2]

Despite Eckert’s leadership over the engineering aspects of the project, the project remained in many respects a collaboration among the Moore School faculty. Thus, one of the senior project engineers, (T.) Kite Sharpless, who had knowledge of radio electronics, proceeded to see if any of his knowledge could be transferred into the domain of electronic computation. Vacuum tubes were already being used for various exploratory studies of FM signals and television broadcasts that operated in the megahertz range. The Moore School was therefore itself a repository for the latest thinking about high frequency vacuum tube engineering. In his laboratory notebooks, Sharpless proceeded to carefully spell out his knowledge about such things as high frequency filters and amplifiers, and its possible application to the design of more responsive circuitry. Especially important were any information he could gather about familiar design tradeoffs in the high frequency domain, and any source of parasitic oscillations that might cause erratic behavior. Although numerical calculation offered the promise of arbitrary accuracy and precision, the work of supporting the electrical abstractions that enabled numerical, or in modern parlance “digital” computation required a good deal of effort in high frequency analog design.[3]

In the end, Pres Eckert and others benefited from outside knowledge. Eckert had maintained that he never directly used the circuit designs supplied to him by officials within the National Defense Research Committee (NDRC), the U.S. civilian science mobilization effort. Taken literally, this may have been true. However, during the early phases of the US war preparations, National Cash Register’s Joseph Desch, who already had several years experience designing digital electronic circuitry, was called upon to help with the early feasibility studies of the atomic bomb. Specifically, he was asked to help NDRC develop high-speed scintillation counters for the critical mass experiments being conducted at the Metallurgical Laboratory in Chicago. In working in the proximity of atomic physicists, Desch was able to approach the problem from a more fundamental level. Drawing also on his prior work, Desch built a scintillation counter that could operate at 1 MHz, and a bistable circuit that operated reliably at 4 MHz.[4] Information about this device was circulated within the NDRC. The ring counters used in the ENIAC may have been sufficiently original to warrant a patent claim. Nevertheless, it was only after the ENIAC engineers were exposed to the broader array of wartime digital electronic developments, and the fundamental design ideas that they embodied, that the team succeeded in operating their circuits at the targeted design speed of 180 kHz.[5]

The second point has to do with the ENIAC “architecture.” This is a topic that I explored previously with Mitch Marcus, then chair of the Department of Computer and Information Science at the University of Pennsylvania.[6] It was our assessment then that the ENIAC was in fact a specific implementation of an idea advanced by the Moore School faculty member Irven Travis in a report written for General Electric. In this report, Travis had suggested that a numerically-based equivalent of the differential analyzer could be built using a series of ganged adding machines, and moreover, that such a device would probably require electronic devices to attain sufficient speed and accuracy. Previously, Travis had led the Moore School’s effort to build a differential analyzer for the Aberdeen Proving Ground during the early 1930s, and he had become something of a local authority on the subject of mathematical instruments. Asked by General Electric to provide a survey of instruments capable of solving various electrical problems, Travis approached the question from a mathematical standpoint and recognized that a numerical alternative existed for the analog methods employed by the differential analyzer. Significantly, Aberdeen, whose augmented research group had been rechristened the Ballistic Research Laboratory (BRL) in 1938, had switched partly back to the use of numerical techniques for compiling ballistic tables.[7]

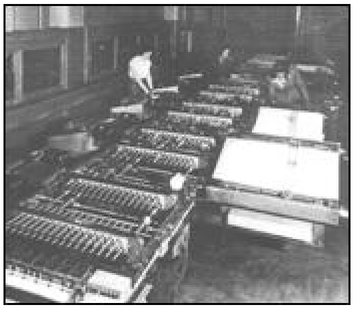

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Figure 3. Moore School differential analyzer (Source: University of Pennsylvania Libraries)

(click to enlarge)

Figure 4. The ENIAC, as subsequently reassembled at the Ballistic Research Laboratory. (Source: US Army Photo)

The ENIAC was clearly influenced by the design of the differential analyzer. John Mauchly had simply been at the right place, at the right time, to take a kernel of an idea and to find a specific, electronic implementation for such a system. Still, it is worth taking a closer look at this diagram from Mauchly and Eckert's original proposal. On the surface, the analogy between this setup diagram and the mechanical design of a differential analyzer are clear. Across the top are the computational elements; the horizontal lines meanwhile look like fixed physical entities, just like the mechanical shafts used to connect the mechanical integrators in a differential analyzer. The diagram itself can be said to have been derived from the setup diagrams used for a differential analyzer.[8]

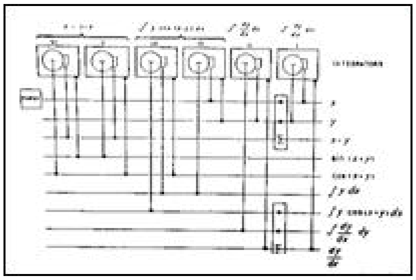

Figure 5. A differential analyzer setup diagram (Source: Hartree's *Calculating Machines* [1947])[9]

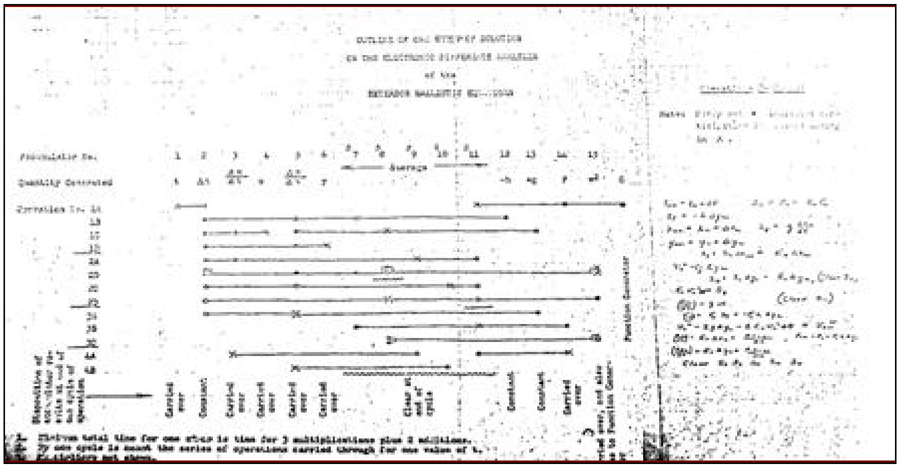

Figure 6. Preliminary setup diagram from 8 April 1943 proposal. Title to the diagram reads, "Outline of One Step of Solution on an Electronic Difference Analyzer of the Exterior Ballistic Equations.[10]

Yet, closer inspection shows a difference. Whereas the mechanical integrators depicted across the top of the diagram each represented a mathematical equation, with the rotating shafts representing mathematical variables and results, this arrangement was inverted in the case of the ENIAC's setup diagram.[11] In the ENIAC diagram, it was the accumulators that held the variables and results. The horizontal lines, then, were not just an unordered column of numerical values, but an implied sequence of mathematical operations. Moreover, each of these operations had to be "programmed" through a specific pattern of interconnections between the ENIAC's various units. The overall sequence of operations, or "program," was based quite directly on the familiar "plan of calculation" used by human computers. At the time, women were being employed by the Moore School to carry out a closely related set of procedures to compile ballistic tables for Aberdeen.[12] Mauchly and Eckert had studied these procedures in drafting their proposal. This, in any event, was the particular amalgam between the differential analyzer and the knowledge and skills of human computers that was incorporated into the ENIAC design.[13]

The work of finding a specific implementation of Travis' proposal was by no means trivial. Nevertheless, the particular approach taken to the ENIAC's design suggests that it is worth revisiting the claim that the design was simply a matter of the war's expediency. From the standpoint of engineering practice, what is most evident is the incremental nature of the design innovations that led to the ENIAC. From Travis, to Mauchly, to Eckert, all of the design ideas were based on taking known methods in analog and human computation, and finding an automated and numerical means of implementing them in mechanical, and then electronic form. This is especially evident in the control system that emerged for the ENIAC. Although the possibility of having a central "Program Control Unit" that could read in a programmed sequence of operations was considered, the decision was made to go with the use of the plug boards and wires that were already a familiar feature of IBM's tabulating machines. Moreover, the ENIAC came to have a distributed control architecture, in which the control circuits were placed on each of the thirty units, much in the way that mathematical equations were set up through the specific configuration of the mechanical integrators and other devices in a differential analyzer.[14]

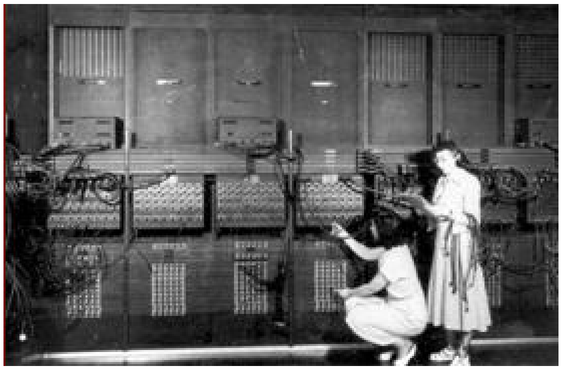

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Figure 7. Closeup of several panels (units) from the ENIAC demonstrating its use of distributed controls (Source: US Army Photo)

If incrementalism explains Mauchly and Eckert's orientation towards the project, this was also re-encoded in the project's organization. Once the decision was made to proceed with the basic model of using a series of ganged adding machines, all of the engineers immediately honed in on specific problems to which they, like Sharpless, felt they could best apply their expertise. Robert Shaw, James Hyman, and others each "adopted" a specific component or problem, ranging from high-speed circuit design, to vacuum tube reliability, to a special function generator (never built) for the non-linear component of the exterior ballistics equation. No one was assigned the task of reviewing the overall design to consider whether there were any serious design alternatives. The ENIAC was, from its outset, an engineering project, and the work was organized along such lines.[15]

(click to enlarge)

Figure 8. Harvard Mark I. Also known as the IBM Automatic Sequence Controlled Calculator. (Source: IBM Archives)

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Figure 9. Bell Relay Computer. This would have been one of the later models installed at the Ballistic Research Laboratory. (Source: US Army Photo)

The fact that the work on the ENIAC proceeded within the confines of certain disciplinary boundaries is especially evident when the work is contrasted against that of Howard Aiken and George Stibitz. Although both worked entirely within the mechanical domain, both Aiken and Stibitz immediately separated out the control unit from the arithmetic unit, and the arithmetic unit from the registers, in developing an approach that was more efficient in terms of the overall use of circuitry. I do not consider this to be the result of any particular brilliance on their part. Unencumbered by the design of the differential analyzer, both Aiken and Stibitz set out to simply automate the work of human computers. Notably, human computers laid out their calculations on the assumption that they were working with a single calculating machine.

Moreover, in working as a technical aid to NDRC's Division 7, and less formally to NDRC's Applied Mathematics Panel (AMP), Stibitz came to occupy a vantage point from which to assemble a much more comprehensive view of computing.[16] Stibitz was trained as a mathematician, and continued to work within the Mathematics Department at Bell Laboratories. As described by David Mindell, Stibitz proceeded to think, and write much more broadly about the different classes of problems that could be solved using his relay computers.[17] Such knowledge was circulated within the NDRC, and did as much to lay the foundation for the interest in electronic computers after World War II.[18]

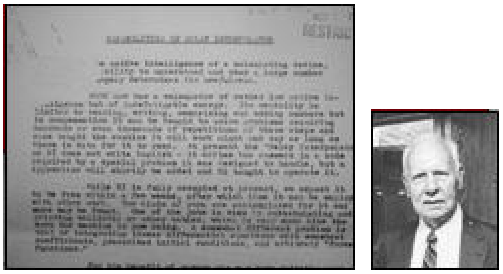

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Figure 10. George Stibitz (Mathematics Department, Bell Telephone Laboratories), "Capabilities of Relay Interpolator," AMP report, 8 November 1943.[19] Inset: A later photograph of George Stibitz. (Source: Virginia Tech)

The final topic, which I will address more briefly, has to do with Eckert's reputation for reliability engineering. Eckert is credited with having discovered the need to have a burn-in period for vacuum tubes, without which the ENIAC could not have sustained useful operations. However, this is exactly the kind of "asymmetric" explanation that has been rejected in the science studies literature, where the end result is used to explain the cause of an innovation. Such explanations tend to lead to highly linear and functionalist accounts of technological innovation. By contrast, a focus on the engineering process, and practice, can provide us with a more contingent account of technological change that simultaneously offers us a more compelling account of how innovation occurs.

In working directly from the laboratory notebooks, it was around January 1944 when the ENIAC project began purchasing significant lots of vacuum tubes in order to build its first pair of accumulators. At this point, the ENIAC was designed using nine standard types of vacuum tubes, and the first lots to arrive demonstrated substantial variability in their operating characteristics. Eckert assigned Sharpless and James Hyman, who at the start of the project was a relatively junior engineer, to evaluate the problem. Drawing on conventional industry practice of testing incoming lots, Sharpless and Hyman designed a meticulous testing regimen whereby they proceeded to test every incoming lot of vacuum tubes to make sure that the devices operated according to their own specifications. This work also involved the design of a specialized testing assembly. Hyman also proceeded to analyze the particular aspects of a disqualified tube that seemed to contribute to its poor performance.[20]

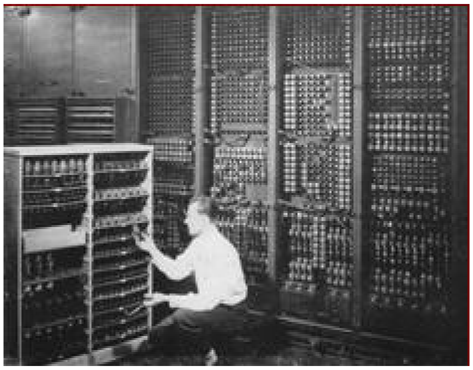

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Figure 11. The ENIAC undergoing maintenance (US Army Photo)

Hyman had tagged all of the tubes that had undergone the incoming test, which is to say all of the tubes in the ENIAC. As the first of the ENIAC's units entered operational testing in June of 1944, it was not much of a stretch to track the tubes that failed during operation, and to record the particular mode of failure. By early 1945, this had expanded into a meticulous program for tracking the life history of all of the tubes, and the particular aspect of the ENIAC's operations, or of a manufacturer's incoming lot, that seemed to contribute to tube failure. The common modes of failure became immediately apparent from their data. Tubes clearly tended to fail during power up and power down. Moreover, tube failures tended to concentrate during the early life of a tube. Whether it was Eckert, Hyman, or someone else who first did so, all that remained was the work of plotting out the time-dependent distribution of failures to determine what an appropriate burn-in period would be for each kind of vacuum tube.[21]

On the other hand, it is important to note that the analysis of vacuum tube failures was only one component of a much broader program for reliability engineering. Whether in the mechanical design of the electrical lines, the use of modular plug-in units, or the systematic reuse of standard circuit design elements, the ENIAC was built using a rather broad array of "best practices" for building reliable electronic systems. It is significant, in this respect, that at the start of the project, Eckert was a recent graduate of the Moore School who had just been indoctrinated into such practices. If these “best practices” were not always as practiced in industry, Eckert’s rigid adherence to the principles of reliability engineering proved essential to the ENIAC’s success.

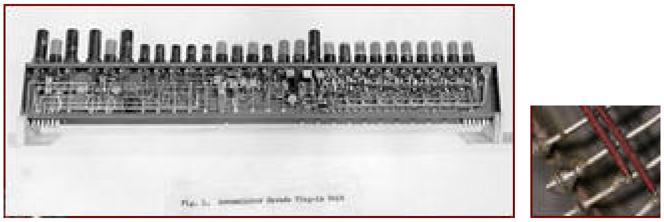
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Figure 12. Close up of an accumulator’s decade ring counter plug-in unit. (Source: Penn Library) Inset: Recent photograph of soldered joints from one of the plug in unit. (Source: University of Pennsylvania, ENIAC Museum)

More broadly, it is worth thinking about what the Moore School, as an institution, brought to the project. The Moore School was not MIT or Stanford, both of which had built their reputation primarily on power systems engineering, and especially the formal and experimental analysis of electrical transients. On the other hand, given their proximity to RCA, as well as the work on radio transmission at Bell Labs, the Moore School had become a substantial center for radio electronics and engineering. This did not include work on the fundamental physical properties of a vacuum tube, as pursued at RCA, nor the extensive orientation towards mathematics that could be found at Bell Labs and MIT.[22] Nevertheless, the Moore School remained a major repository of knowledge for best practices in electronic circuit design. This is what the ENIAC engineers brought to the development of the electronic computer.


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Figure 13. The Moore School of Electrical Engineering (Source: University of Pennsylvania, Engineering Operational Services)

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Figure 14. RCA Laboratories (Source: David Sarnoff Library). Inset: RCA advertisement, 1939. (Source: www.coutant.org)

From a somewhat more theoretical standpoint, the three stories presented in this talk all speak to the current interest in the "circulation of knowledge" within science studies circles. This is something that intellectual historians may feel they have done all along. While this is true in part, the new work has certainly benefited from the conceptual detour brought about by the constructivist turn, in which equal attention is now paid to material culture and the skilled practices of science and engineering. Moreover, while scholars have turned to the circulation of knowledge as a means of understanding technical innovation, the examples presented here should make it clear that disciplinary practices, and the knowledge embedded in artifacts, do as much to constrain innovation as to enable it—generally in the same instance. This is not to say that disciplinary boundaries are absolute. Mauchly himself was trained as a physicist, not an electrical engineer, and he assembled much of the relevant knowledge for the ENIAC during his early, peripatetic career. Yet, the knowledge he accumulated was selective; he was also influenced by the differential analyzer design. Moreover, once his ideas were brought into the disciplinary and organizational context of the Moore School of Electrical Engineering, work on the ENIAC proceeded according to a fixed notion of the problem with no immediate attention given to other possibilities.

This is not said to denigrate Mauchly's contributions, nor those of Eckert and the other Moore School engineers. I myself was involved with the ENIAC's "50th anniversary celebration." And there are valid reasons for preserving the myth of the heroic inventor, most of it having to do with the recruitment and socialization of students into the engineering profession. Yet, ultimately, we must be careful not to convey the wrong model of innovation to our students. Commemorations become inextricably tied to matters of intellectual property, and this leads all too easily to linear and functionalist accounts of technological change. From a pedagogic standpoint, I suspect, in the end, that what we want to convey to our students is a better feel for the actual process of innovation. The constructivist tradition in science and technology studies suggests that close attention to the material culture and practice of science and engineering will make it more likely that this can happen.

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Notes

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[1] In this article, all figures are reproduced as a low-resolution thumbnail that is used to represent the original images. Where available, live links to full resolution images are provided under the label, "(click to enlarge)."

[2] [Arthur Burks], "Positive Action Ring Counter: The Eckert counter," Report for Project PX, 17 August 1943. ENIAC Papers, box 22, folder 7. University of Pennsylvania, University Archives and Records Center, Philadelphia, PA. (Hereafter, "ENIAC Papers")

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[3] [T.K. Sharpless,] "Coupling Circuits. Report for Project PX," in T.K. Sharpless, Laboratory notebook, Serial N. Z14, entry for 26-28 July 1943, p. 3. ENIAC Papers, box 22, folder 5. See also entries for 20 November 1943, p. 24; 15 December 1943, p. 33; and 9 May 1944, p. 65.

[4] Colin Burke, *Information and Secrecy: Vannevar Bush, Ultra, and the Other Memex* (Metuchen, NJ: Scarecrow Press, 1994), 89-97, 206.

[5] In actual use, the ENIAC operated with a 100 kHz clock. All circuits were tested at 180 kHz so as to provide a substantial operating margin and to allow for the degradation of the circuitry. P.N. Gillon to J.R. Desch, 13 July 1943; P.N. Gillon to Harold Hazen, 19 August 1943; H.L. Hazen to Irven Stewart, 26 August 1943; P.N. Gillon to J.G. Brainerd, 7 September 1943; SHC [Samuel Caldwell] to HH [Harold Hazen], 13 September 1943; Plaintiff's Trial Exhibit Nos., 1593, 1633, 1635, 1653, and 1657. All ENIAC Papers, box 22, folders 7 and 9; Arthur Burks and Alice Burks, “The ENIAC: First General-Purpose Electronic Computer,” *Annals of the History of Computing* 3 (October 1981): 391.

[6] Mitchell Marcus and Atsushi Akera, “Exploring the Architecture of an Early Machine: The Historical Relevance of the ENIAC Machine Architecture,” *IEEE Annals of the History of Computing* 18/1 (1996): 17-24.

[7] Alice Burks and Arthur Burks, *The First Electronic Computer: The Atanasoff Story* (Ann Arbor: University of Michigan Press, 1988) 107; Burks and Burks, "The ENIAC," 314; Herman Goldstine, *The Computer from Pascal to Von Neumann* (Princeton, NJ: Princeton University Press, 1993/1972), 134.

[8] University of Pennsylvania, Moore School of Electrical Engineering, "Report on an Electronic Difference Analyzer," 8 April 1943. Defendant's Trial Exhibit 3361. ENIAC Papers, box 72, folder 12; Burks and Burks, “The ENIAC,” 319, 327, 343-44.

[9] Douglas Hartree, *Calculating Machines: Recent and Prospective Developments and their Impact on Mathematical Physics* (Cambridge: Cambridge University Press, 1947). Reprinted in Burks and Burks, “The ENIAC,” 319.

[10] Source: University of Pennsylvania, Moore School of Electrical Engineering, "Report on an electronic difference analyzer," 8 April 1943, p. 20A. Defendant's Trial Exhibit 3361. ENIAC Papers, box 72, folder 12.

[11] This analysis pertains to the setup diagram and its representation, and not the physical differential analyzer. Given the mode of operation of analog computing instruments, it could be said that the state (variables and results of computation) was held as much in the rate of rotation of the integrators as in the rotating shafts.

[12] Mauchly and Eckert anticipated that the ENIAC would be able to use a somewhat simpler algorithm to compute an exterior ballistics trajectory, in using electronic speeds and a smaller interval of calculation to compensate for the reduced accuracy of the algorithm. Using the simpler algorithm reduced the number of units the ENIAC required.

[13] University of Pennsylvania, Moore School of Electrical Engineering, "Report on an electronic difference analyzer," 8 April 1943. Defendant's Trial Exhibit 3361. ENIAC Papers, box 72, folder 12.

[14] Ibid., 7.

[15] The work done by these project engineers may be found in their laboratory notebooks, filed with the ENIAC Papers, box 22, various folders.

[16] Especially significant was AMP Study NO-92, conducted at the request of the Naval Proving Ground at Dahlgren, to provide them with a survey the different “analyzers” they should

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consider acquiring for their own computing facility. This study gave Stibitz an opportunity to compare his work on relay computers against the Harvard Mark I, and to compare digital and analog computing techniques. “Meetings of the Applied Mathematics Panel, January 27, 1943 – April 24, 1946,” Work diaries, entry for 20 December 1943, 1 and 15 May 1944 (hereafter, “AMP Meetings”). RG 227, Records of the Applied Mathematics Panel, General Records, 1942-46 (hereafter, “AMP Records”), box 1, folder: “AMP Meetings, 1943-46.” National Archives and Records Administration, National Archives II, College Park, MD (hereafter, NA-II); David Hedrick (Commanding Officer, NPG-Dahlgren) to Chief of Bureau of Ordnance, 22 September 1944; and George Stibitz, “Final Report of Committee on Computing Aides to Naval Ballistics Laboratory,” 28 April 1944. Both Harvard University, Computation Laboratory, Correspondence Files for H.H. Aiken, box 1, folder: “Correspondence 1944-45.” Harvard University Archives, Cambridge, MA.

[17] David Mindell, *Between Human and Machine: Feedback, Control, and Computing Before Cybernetics* (Baltimore: Johns Hopkins University Press, 2002), 302-03; G.R. Stibitz. “Relay Interpolator as Differential Analyzer,” Report, 19 June 1943. NA-II, RG 227, Division 7—Records of Chief and Members of Sections, 1940-1946, box 5, folder: “Relay Interpolator”; George Stibitz to Stephen Stark, 24 August 1943; George Stibitz to Warren Weaver, Memo, 24 August 1943 and 6 November 1943; Warren Weaver to distribution, Memo, 2 December 1943. All NA-II, RG 227, Office Files of Warren Weaver, 1940-1946, box 5, folder: “”Stibitz, GR—Correspondence.”

[18] While this is beyond the scope of this paper, the various technical developments during World War II suggest that there was nothing especially novel about a stored program computer. While it may be true that those associated with the ENIAC project discovered the need for an improved programming system as they thought about interconnecting and reconnecting the ENIAC for specific problems, by the time they gave serious thought to the issue, the programming systems employed by the Harvard Mark I and the Bell relay computers would have been familiar to them. The necessity of storing the programs within the memory system resulted from the need to have an electrical system capable of stepping through a program at electronic speeds. While a programming system involving an external system of electrical relays was considered during the early discussions of the EDVAC design, this quickly gave way to the thought of using the mercury delay line memories to store both the program and the data. At the time, there was not much thought given to this step. It was simply a matter of expediency of not having to develop an entirely separate memory system for the programs. Atsushi Akera, “Calculating a Natural World: Scientists, Engineers and Computers in the United States, 1937-1968” (PhD dissertation, University of Pennsylvania, 1998), 124-25.

[19] Source: NA-II, RG 227, AMP Records, box 8, folder: “Stibitz, GR”.

[20] H. James, Laboratory notebook, Serial No. 33, entries for 17 January 1944, p. 95; "Summary of 6Y6 test of 99 tubes," 18 January 1944, p. 98; "PX tube checker," 5 January 1944, p. 88. See also early entries in Sharpless' notebook, Serial No. Z14. ENIAC Papers, box 2, folders 5 and 8.

[21] H. James, Laboratory notebook, entries for n.d., p. 120; 14 February 1945, p. 136.

[22] Mindell, *Between Human and Machine,* chapters 4 and 5.