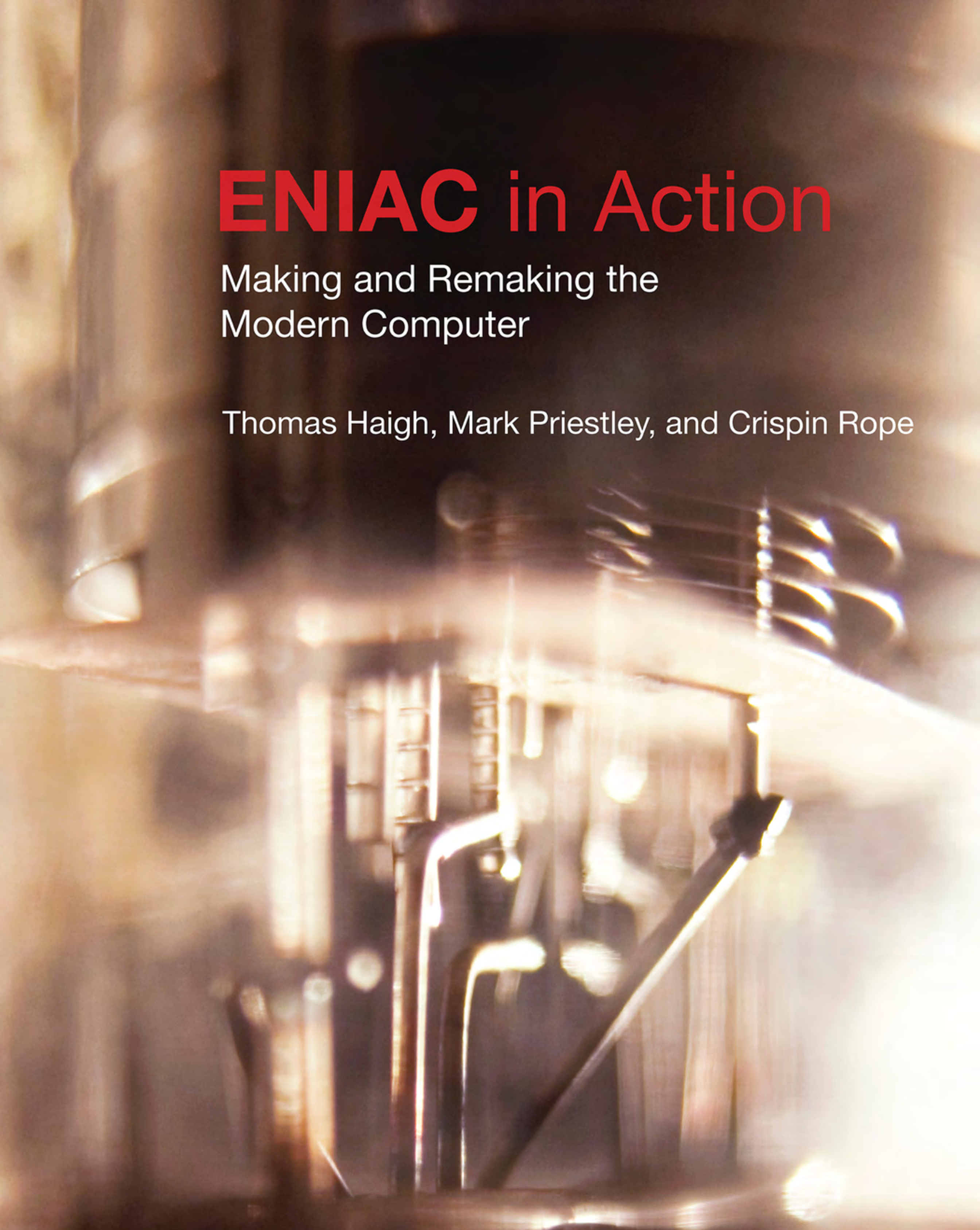

ENIAC in Action

Making and Remaking the Modern Computer

Thomas Haigh, Mark Priestley, and Crispin Rope

ENIAC in Action

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ENIAC in Action

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Thomas Haigh, Mark Priestley, and Crispin Rope

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dedicated to Douglas R. Hartree,
who could do a great deal with ten million multiplications

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Peggy Kidwell of the National Museum of American History was particularly helpful in pointing us toward the earliest known use of the term "stored program" and in helping us clarify the locations and the ownership of many surviving parts of ENIAC. Kim D. Todd at the Jean Jennings Bartik Computing Museum provided several images, including what may be the earliest surviving record of an ENIAC set-up used in practice. George Dyson and Marina von Neumann Whitman shared with us unpublished material from the latter's personal collection of papers concerning Klara von Neumann. Anne Fitzpatrick, Steve Aftergood, Robert Seidel, J. Arthur Freed, and Alan B. Carr all did what they could to help us navigate the maze of restrictions surrounding access to historical materials from Los Alamos, though alas our Freedom of Information Act requests have yielded no fruit more than two years after they were submitted.

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Portions of chapters 8 and 9 were previously published in Haigh, Priestley, and Rope, “Engineering ‘The Miracle of the ENIAC’: Implementing the Modern Code Paradigm,” *IEEE Annals of the History of Computing* 36, no. 2 (2014): 41–59.

Portions of chapters 7 and 11 were previously published in Haigh, Priestley, and Rope, “Los Alamos Bets on ENIAC: Nuclear Monte Carlo Simulations, 1947–48,” *IEEE Annals of the History of Computing* 36, no. 3 (2014): 42–63.

List of Recurring Characters

A number of people make repeated but short appearances in this book, several of them under multiple names because of marriage. To minimize confusion without making endless re-introductions, we have prepared this list.

Barnes, Gladeon Marcus
Chief of Research and Development for the Ordnance Department, and therefore responsible for Aberdeen Proving Ground, of which the Ballistic Research Laboratory (BRL) was a part. Represented the Ordnance Department at the ENIAC launch event.

Bartik, Jean
Married name of Betty Jean Jennings.

Bilas, Frances
One of the first of the ENIAC operators selected in 1945, having worked as a computer and differential analyzer operator for the BRL since 1942. Married Homer Spence.

Brainerd, John Grist
A senior member of the faculty of the University of Pennsylvania's Moore School of Electrical Engineering who was designated director of the ENIAC project.

Burks, Arthur W.
A mathematician turned philosophy PhD turned ENIAC engineer who made substantial contributions to ENIAC's design, produced the first detailed plans for the trajectory computations, and later wrote extensively on the early history of electronic computing.

Clippinger, Richard
A mathematician who was employed at the BRL from 1944 to 1952. He became involved with ENIAC in 1946 as a user interested in simulating supersonic wind flow, and later took part in planning the conversion of ENIAC's programming system.

Cunningham, Leland
A Harvard University astronomer who worked at the BRL during World War II. He helped to shape ENIAC through its design process and served on the BRL's Computations Committee to plan ENIAC applications.

Dederick, Louis S.
A senior BRL civilian scientist, appointed head of the BRL's Computing Laboratory in 1945. He retired from the laboratory in 1953.

Eckert, John Presper, Jr.
A young electronic engineer who led the detailed design and construction of ENIAC as "laboratory chief." One of the two ENIAC inventors credited in its patent. Left the Moore School in 1945 to co-found the first computer company.

Gillon, Paul
A computational specialist and member of the BRL staff who was responsible for the BRL's joint development of differential analyzers with the Moore School. Herman Goldstine's direct supervisor during the early part of ENIAC development, he was later a supporter of the project from within the Army's Office of the Chief of Ordnance.

Goldstine, Adele Katz
A mathematician who trained and recruited human computers and who in 1947 drafted an early plan for the conversion of ENIAC to its new programming mode. Wife of Herman Goldstine.

Goldstine, Herman Heine
A mathematician assigned as the BRL's liaison to the Moore School, initially to oversee the human computers working there. He was the Army's primary liaison to the ENIAC project and was deeply involved in its daily progress. Later he worked with John von Neumann at the Institute for Advanced Studies in Princeton. Husband of Adele Goldstine.

Holberton, Frances Elizabeth "Betty"
Married name of Elizabeth "Betty" Snyder.

Holberton, John
A BRL staff member who was selected in 1945 to head ENIAC operations, which he did during its time at the Moore School and after its move to Aberdeen. Married Elizabeth "Betty" Snyder.

Jennings, Betty Jean
One of the initial cohort of ENIAC operators hired by the BRL in 1945. Leader in 1947–48 of a contract programming group that worked on the plans to convert ENIAC to its new programming mode. Became Jean Bartik upon marriage in 1946.

Lehmer, Derrick Henry
A mathematician with a particular interest in prime numbers. He spent part of World War II at the BRL and served on the computations committee responsible for planning ENIAC applications.

Lichterman, Ruth
Hired by the BRL as a human computer, she became one of the first ENIAC operators in 1945. She became Ruth Teitelbaum upon marriage.

Mauchly, John W.
A physicist and a member of the Moore School's faculty who instigated the ENIAC project. One of the two ENIAC inventors credited in its patent. Left the Moore School in 1945 to co-found the first computer company.

McNulty, Kathleen Rita "Kay"
Hired by the BRL as a computer in 1943, she operated the differential analyzer before becoming one of the initial cohort of ENIAC operators in 1945. Married John Mauchly in 1948.

Metropolis, Nicholas Constantine
A physicist and Manhattan Project veteran who remained active after World War II in developing computational methods at Los Alamos while on the faculty of the University of Chicago. In 1948 he returned to Los Alamos, where he led development of its first electronic computers. He reconfigured ENIAC's programming mode in 1948 immediately before the first computerized Monte Carlo simulations were run.

Pender, Harold
Dean of the Moore School, where ENIAC was created under contract to the BRL.

Sharpless, Thomas Kite
An ENIAC design engineer, nearly always referred to as T. Kite Sharpless.

Simon, Leslie E.
A scientist who served as director of the BRL and was responsible for overseeing ENIAC's construction and use.

Snyder, Frances Elizabeth "Betty"
One of the initial cohort of ENIAC operators hired by the BRL in 1945. Left the BRL in 1948. Married John Holberton.

Spence, Homer
Began maintenance work on ENIAC in 1945 as an enlisted soldier. Returned as a civilian employee to the BRL, where he then oversaw maintenance work. Married Frances Bilas in 1950.

Teller, Edward
Physicist, Manhattan Project veteran, and co-inventor of the hydrogen bomb.

Travis, Irven
Moore School faculty member since 1931. In 1940 proposed construction of an electronic differential analyzer with close parallels to the later ENIAC proposal. After returning to the Moore School from a wartime assignment, he oversaw contract research, including ENIAC and EDVAC work.

Ulam, Stanislaw M.
Physicist, Manhattan Project veteran, one of the originators of the Monte Carlo method, and co-inventor of the hydrogen bomb.

von Neumann, John
A mathematician who was involved in the ENIAC project from approximately August 1944 on. Helped to shape plans for its successor, EDVAC, as expressed in the hugely influential "First Draft of a Report on the EDVAC." Also credited with the idea for converting ENIAC to EDVAC-like operation, he was responsible for bringing several teams from Los Alamos to Philadelphia, and later to Aberdeen, to work with ENIAC. Husband of Klara von Neumann.

von Neumann, Klara
Coded and helped to run a series of Monte Carlo simulations run on ENIAC for Los Alamos between 1948 and 1950. Wife of John von Neumann.

Archival Collections Used

Thanks in large part to research associated with the ENIAC litigation that was concluded in the 1970s, many ENIAC documents are held in more than one of the institutional and personal collections listed below. Where we can do so, we have cited the collection in which an original copy of a particular document is held.

AWB-IUPUI
Arthur W. Burks Papers, Institute for American Thought, Indiana University–Purdue University Indianapolis. The papers are stored in file drawers. Because the folders are not numbered, no precise locations can be given. Finding aid: http://liberalarts.iupui.edu/iat/uploads/docs/Arthur_Burks-Finding_Aid-Jan2012.pdf.

AWB-NCSU
A. Wayne Brooke Collection, 1948–1986, Special Collections, North Carolina State University, Raleigh. Each citation is followed by a box number and a serial number. Finding aid: http://www.lib.ncsu.edu/findingaids/mc00268.

ETE-UP
ENIAC Trial Exhibits, Master Collection, 1864–1973, University of Pennsylvania Archives and Records Center, Philadelphia. Finding aid: http://www.archives.upenn.edu/faids/upd/eniactrial/eniac.html. A searchable database can be used to locate items by title and author. This is a microfilm collection consolidating photocopied trial materials from the University of Pennsylvania, the Charles Babbage Institute, and the Hagley Museum and Library. The microfilms are also accessible at those institutions. When the paper copies are held at University of Pennsylvania, we generally cite ETR-UP instead as ETE-UP.

ETR-UP
ENIAC Patent Trial Collection, 1864–1973, University of Pennsylvania Archives and Records Center, Philadelphia. Finding aid: http://www.archives.upenn.edu/faids/upd/eniactrial/upd8_10.html.

GRS-DC
Papers of George R. Stibitz, 1937–1979, Dartmouth College, Hanover, New Hampshire. Each citation is followed by a box number and a folder name. Finding aid: http://ead.dartmouth.edu/html/ml27_fullguide.html.

HHG-APS
Herman Heine Goldstine Papers, American Philosophical Society, Philadelphia. Each citation is followed by a series number and a box number. No finding aid is available online, but an unpublished draft of a finding aid is available from the archivists of the American Philosophical Society.

HHG-HC
Herman H. Goldstine Collection, 1941–1971, archives, Hampshire College, Amherst, Massachusetts. Each citation is followed by a box number. Finding aid: http://asteria.fivecolleges.edu/findaids/hampshire/mah1.html.

JGC-MIT
Papers of Jule G. Charney, MC.0184, Massachusetts Institute of Technology Archives, Cambridge. Each citation is followed by a box number and a folder number. Finding aid: http://libraries.mit.edu/archives/research/collections/collections-mc/mc184.html.

JvN-LOC
Papers of John von Neumann, Manuscripts Division, US Library of Congress, Washington. Each citation is followed by a box number and a folder number. Finding aid: http://lccn.loc.gov/mm82044180.

JWM-UP
Papers of John W. Mauchly, University of Pennsylvania Kislak Center for Special Collections, Rare Books and Manuscripts, Philadelphia. Processing in progress at the time of writing.

KvN-MvNW
Papers related to Klara von Neumann retained in the personal collection of Marina von Neumann Whitman. We did not see the originals; we worked from extracts transcribed by Whitman and scans sent to us by George Dyson. The originals have subsequently been donated as part of the Marina von Neumann Whitman Papers, 1946–2013, Schlesinger Library, Radcliffe Institute for Advanced Study, Harvard University, Cambridge, Massachusetts.

MSOBM-UP
Moore School of Electrical Engineering, Office of the Business Manager Records, 1931–1948, UPD-8.3, University Archives and Records, University of Pennsylvania, Philadelphia. Each citation is followed by a box number and serial number. Finding aid: http://www.archives.upenn.edu/faids/upd/upd8_3invtry.pdf.

MSOD-UP
Moore School of Electrical Engineering, Office of the Director Records, 1931–1948, UPD 8.4, University Archives and Records, University of Pennsylvania, Philadelphia. Each citation is followed by a box number and a folder name. Finding aid: http://www.archives.upenn.edu/faids/upd/upd8_4invtry.pdf.

NARA-ENIAC
Records Relating to the Development and Use of the Electronic Numerical Integrator and Computer (ENIAC), 1943–1947, National Archives at Philadelphia. Each citation is followed by a box number and a folder number. Finding aid: http://research.archives.gov/description/636248.

SMU-APS
Stanislaw M. Ulam Papers, American Philosophical Society, Philadelphia. Each citation is followed by a series number and a folder name. Finding aid: http://www.amphilsoc.org/mole/view?docId=ead/Mss.Ms.Coll.54-ead.xml.

UV-HML
Sperry Rand Corporation, UNIVAC Division records, Accession 1825.I, Hagley Museum and Library, Wilmington, Delaware. Each citation is followed by a box number and a folder name. Finding aid: http://findingaids.hagley.org/xtf/view?docId=ead/1825_I.xml.

Introduction

In October of 1946, Douglas Hartree took up the post of Plummer Professor of Mathematical Physics at the University of Cambridge. His inaugural lecture was published the next year as an influential little book on recent developments in "calculating machines."[1] A few months earlier Hartree had been visiting the University of Pennsylvania, where he had a rare opportunity to use the newly constructed Electronic Numerical Integrator And Computer (ENIAC), an urgent wartime project rushed from conception in 1943 to completion in 1945 under the direction of J. Presper Eckert Jr. and John W. Mauchly. Hartree's lecture centered on the opportunities for science presented by this electronic marvel. Its "speed of operation" was "of the order of a thousand times faster than anything else at present available." Thus, "a calculation involving ten million multiplications may take only about nine hours." Hartree noted with wry understatement that "one can do quite a lot with ten million multiplications."

The present book is about how and why a small group of mathematicians, scientists, engineers, and Army administrators came together to propose, authorize, and design the unusual machine. It is also about the women and men who built, programmed, and operated ENIAC, and about the uses scientists found for all those millions of multiplications. Access to millions (and eventually billions and trillions) of automatically sequenced arithmetic and logical operations transformed the practice of science during the second half of the twentieth century. ENIAC established the feasibility of high-speed electronic computing, demonstrating that a machine containing many thousands of unreliable vacuum tubes could nevertheless be coaxed into uninterrupted operation for long enough to do something useful.

During an operational life of almost a decade ENIAC did a great deal more than merely inspire the next wave of computer builders. Until 1950 it was the only fully electronic computer working in the United States, and it was irresistible to many governmental and corporate users whose mathematical problems required a formerly infeasible amount of computational work. By October of 1955, when ENIAC was decommissioned, scores of people had learned to program and operate it, many of whom went on to distinguished computing careers. Within limits imposed by its design, ENIAC could be programmed to combine its basic computational operations in whatever order was needed for the problem at hand. It could select a course of action on the basis of results it had so far obtained—for example, to calculate a shell's trajectory only to the point where the shell hits the ground. Previous calculating devices had either required human intervention at such moments or been limited to problems of a particular kind. That new capability gave ENIAC great flexibility. Among other things, it calculated tables of sines and cosines and tested for statistical outliers, simulated explosions of hydrogen bombs, plotted the trajectories of bombs and shells, searched for prime numbers, ran the first numerical weather simulations, modeled the flow of air at supersonic velocities, and analyzed data from experimental firings of captured German V-2 rockets.

This is the first scholarly book devoted to ENIAC and the first comprehensive examination of its use as a scientific instrument. But ENIAC has never been an obscure machine. Widely publicized at the time of its creation, it was later at the center of a series of high-profile legal proceedings, and it figures prominently in standard histories of computing. It is still frequently written about, and it features in a number of major museum displays. Yet previous accounts have neglected many aspects of ENIAC's story in favor of casting it in one of two traditional roles: either as a candidate for the title of the "world's first computer" or as merely one of a series of steps leading to development of the modern computer. In recent years discussion has focused on ENIAC as the site of another "first": the workplace of the first computer programmers. All three narratives focus almost entirely on episodes in ENIAC's initial development and experimental use, as the turning point in computer design or programming practice is assumed to have come during that phase. Much less has been written about ENIAC as a physical machine changing over time, as a busy workplace, or as a scientific instrument.

Books that focus on material objects often signal the importance of their subjects by presenting them as inflection points in world history. The titles of dozens of books have tried to lure a broad audience to an obscure topic by touting an idea, a fish, a dog, a map, a condiment, or a machine as having "changed the world." George Dyson recently argued for John von Neumann's computer, built at the Institute for Advanced Studies in Princeton a few years after ENIAC, as the "point source" of origin for "the digital universe." Similar claims might be made at least as persuasively for ENIAC: Was ENIAC an essential agent in the construction of the modern world, like cod, salt, or the Irish? Were its creators miraculously ahead of its time, as Ada Lovelace, Leonardo da Vinci, and Alan Turing are said to have been? Was it the work of a lone genius defying the lazy wisdom of inbred elites?

One of the luxuries of writing an obscure academic book is that one is not required to embrace such simplistic conceptions of history. As the title *ENIAC in*

Action suggests, this book focuses on the many different ways in which ENIAC was used. It is a nod to Bruno Latour's *Science in Action*, a foundational work of science studies.[2] Like Latour, we are interested in how artifacts, such as ENIAC and its components, act in conjunction with humans. The concept of action, in this broad sense, runs through the entire book. It applies not only to the use of the physical ENIAC to carry out computations but also to the use of initial sketches of ENIAC to mobilize resources at the beginning of the project and to more recent attempts to enlist ENIAC to bolster the participation of women in computing. Reducing this rich history to an argument that some particular feature of ENIAC "changed the world" would sacrifice a great deal. Instead we try to position ENIAC within various historical chains connecting earlier technologies and practices to later ones. We document these connections not only in the area of computer design but also in the areas of programming practice, computing labor, and scientific practice.

We tell ENIAC's story in a broadly chronological way, moving through invention, construction, use, and modification to obsolescence, but from a number of different perspectives. Each perspective offers a different view of what ENIAC was or is, and thus of why it matters. In the rest of this introduction we introduce some of those perspectives, sketching how our approach differs from previous accounts and situating our work on ENIAC within several distinct historical traditions.

ENIAC as a Machine of War

The electronic computer was, like radar and the atomic bomb, a technology developed for and during World War II, a period of exceptionally rapid innovation. For example, nearly every military aircraft that was flying in 1939 was obsolete before the end of the war. The Mitsubishi Zero fighter dominated early engagements, but by the war's end it was fit only for kamikaze duty. Advances in anti-submarine warfare obliterated the formerly invincible German U-boat fleet. Communications and cryptography advanced dramatically. Nations transformed themselves. Industrial production quickly shifted from civilian to military needs, new goods and foodstuffs were introduced to replace those that were unavailable because of wartime disruption, and government bureaucracies were established and staffed in record time. Boats and planes were mass produced on a scale unknown before or since. Technologies moved from lab to battlefield in months. People everywhere were working harder than usual, sleeping less, and looking for ways to get things done without delay. All this created opportunities for the young and ambitious to win approval for unconventional ideas. The war ended after two bombs destroyed two cities, an unprecedented leap in destructive power.

Many of the apparently sudden breakthroughs of the war resulted from the application of money and enthusiasm to implement ideas that had been proposed years earlier, only to languish during the Great Depression. The jet engine, for example, had been patented in 1930 but was not incorporated into a fighter until 1944. Amateur rocket enthusiasts had been promoting their technology ever since the 1920s, but only the war provided German rocket builders with the money and slave labor they needed to push the technology into practical use. The atomic bomb depended on recent advances in theoretical and experimental physics, but could be built only thanks to the labor of many thousands of people within specially constructed industrial cities. Such a commitment of effort would have been unlikely in peacetime.

ENIAC was small by the emerging standards of postwar "big science," or even in comparison to the largest scientific projects launched by the government during the war.[3] The Manhattan Project alone cost about 4,000 times as much. Historians have focused on the wartime Office of Scientific Research and Development (OSRD), headed by Vannevar Bush, as a crucial institution in bringing thousands of scientists, the government, and vast sums of money together in pursuit of military advantage. The Massachusetts Institute of Technology alone received $117 million in research funding during the war. We do not have much to say in this book about the roles of OSRD and other high-profile agencies in supporting, opposing, or shaping ENIAC. Other historians have ably documented these connections, and we have little to add to their accounts.[4] The construction of ENIAC was justified by a specific wartime need—to produce firing tables at a time when human computational labor was scarce—and was made possible by the huge sums of money that the federal government allocated to the Army. Nevertheless, we see it as fundamentally a bottom-up, local initiative in which staff members of the University of Pennsylvania's Moore School of Electrical Engineering allied themselves with the management of the Ballistic Research Laboratory, and with that lab's patrons in the Army's Ordnance Department, to launch a project of mutual interest.[5]

If ENIAC had never existed, history would surely have followed some other path to the development of computer technology. So we are particularly concerned with aspects of ENIAC's design and use that were shaped by its specific context as a machine rushed into existence during wartime. ENIAC is a milestone on only one of many possible paths to the modern computer, and that particular path is one that would never have been taken in peacetime. Every aspect of ENIAC was influenced by the war: the task for which it was crafted, the design compromises made to produce it more quickly, the scale on which it was constructed, even the way it was staffed and operated. Without the war, no one would have built a machine with its particular combination of strengths and weaknesses.

Our story has more to say about changes in scientific practice during the twentieth century's wars than it does about the development of federal science bureaucracies. ENIAC belongs to the tradition, reaching back as far as Charles Babbage, of devices intended to reduce the labor involved in producing mathematical tables. In ENIAC's case, these were artillery firing tables, affected by tactical developments in World War I that greatly increased the computational challenge of producing them. These tables were still needed after World War II: we estimate that ENIAC spent at least a fifth of its productive life calculating trajectories for them.[6]

But ENIAC's more profound contributions to advances in military science and technology came with Cold War work that would have been prohibitively expensive to attempt by hand. ENIAC simulated explosions of atomic and hydrogen bombs, airflow at supersonic speeds, and designs for nuclear reactors. With the considerable assistance of John von Neumann, it established the digital computer as a vital tool within the emerging military-industrial-academic complex carrying out cutting-edge research and development work during the early years of the Cold War. A few years later, IBM launched its first commercial computer, the Model 701, as the "defense calculator" and sold it almost exclusively to defense contractors. The United States Government even managed the delivery queue for IBM, making sure that computers were dispatched first to the firms doing the most important work.[7]

ENIAC was particularly important as a test-bed for algorithmically driven simulation, a fundamentally new approach to modeling. The Monte Carlo simulations carried out from 1948 to 1950 on behalf of Los Alamos were landmarks in the history of scientific practice as well as in the history of computer programming. The historian of physics Peter Galison made ENIAC's role in the development of computer simulation famous, but in chapters 8 and 9 we provide the first clear and in-depth exploration of exactly what the simulations did and, drawing on the dissertation work of Anne Fitzpatrick, illuminate the contributions they made to the progress of the atomic weapons program.[8]

ENIAC as the "First Computer"

New acquaintances learning that someone is a historian of computing often ask "What was the first computer?" The case for caring about ENIAC has usually been expressed a "first" of some kind, and it is ENIAC's status as the "first computer" that continues to dominate public discussion, for example in the "talk" section of its Wikipedia page, reviews posted on Amazon of books related to early computers, or the comments threads of online news articles. Feuds between the supports of rival claimants seem to return to life however assiduously historians try to steer discussion in more productive directions.[9]

Some firsts record historical events understood by participants and spectators as dashes to a defined goal, making the order in which contestants reach the finish line crucial. The celebrated "races" to get humans to the North Pole, the summit of Everest, the surface of the moon, or moving faster than the speed of sound fall into this category. The question of priority can also be of great importance in patent law, and in fact legal proceedings around ENIAC's patent profoundly shaped discussion of its place in history. Yet the computer projects of the 1940s have only in retrospect been perceived as races toward a well-defined goal. Thus, questions of influence and legacy are more historically revealing than those of priority. For example, while we show that in 1948 ENIAC was reconfigured to become the first computer to run a program written in the modern code paradigm we also found that no one who was involved appears to have seen that as particularly momentous at the time and that it did not have a discernible direct influence on other computer projects.

ENIAC was not the first electronic digital computer, even though for some decades it was generally believed to have been. The basic idea of a programmable computer is usually traced back a century earlier—to Charles Babbage, who worked for years on the design of a hand-cranked "Analytical Engine" but did not build it. In Germany, Konrad Zuse built an automatic mechanical calculator in his family's apartment in the 1930s, and during World War II he was given government resources to create a variety of successors based on relay technology. Even the use of electronic devices to hold and manipulate numbers was not unprecedented. From 1937 to 1942, the physicist John Atanasoff worked to build an electronic computer that would be able to solve systems of simultaneous linear equations. It never quite worked, but that failure is attributable to its external storage system (intended to burn intermediate results onto paper) rather than to its electronic components.[10]

Beyond this well-documented series of experimental machines lay a variety of special-purpose digital devices designed for different applications. Adding machines, calculating machines, and cash registers represented numbers digitally using systems of interlocking cogs. Punched-card machines stored data as patterns of holes in small rectangular cards, and by the 1930s letters as well as numbers could be represented. Machines specialized for particular tasks, such as sorting or punching cards, were configured by setting switches or wiring plugboards.

The first fully operational electronic digital computer, however, was a British machine, or rather a series of machines, called Colossus. Like ENIAC, Colossus was intended to address specific challenges and was shaped profoundly by the urgency of war. It was developed at the Post Office Research Establishment in London and deployed, under great secrecy, on a sprawling private estate in southern England that had been converted to house a scientific assault on the cyphers that the Germans were using to protect communications. Secrecy was paramount, since the codes could easily be modified if the Germans began to suspect that their contents were no longer secure. The very existence of Colossus was thus top secret throughout the war (and, thanks to the instinct for secrecy prevalent in the intelligence community, for decades afterward). Its creators were unable to take public credit for their historic achievements, and the machines, their blueprints, and other records of the project were systematically destroyed after the war.

Like Atanasoff's computer, the Colossus machines are usually classed as special-purpose machines confined to a single application, although they have widely been recognized as "programmable" because they could be reconfigured to apply different sequences of steps to decryption work.[11] Because of the secrecy surrounding it, Colossus had no influence on the ENIAC project. Even in Britain it had only an indirect and underappreciated influence on later developments, as its veterans were not able to explain the source of their ideas or to justify their confidence in particular techniques. Tommy Flowers, Colossus' primary designer, received little recognition until the very end of his life. Even after Colossus was embraced as part of Britain's national heritage, many still assumed that it had been Alan Turing's creation.

Scholars addressed the continuing feuds between the creators of these and other early computers by agreeing on the appropriate series of adjectives to insert between the words "first" and "computer" to reflect the unique contribution of each pioneer. Introducing a conference devoted to early computers, the historian Michael Williams asked his colleagues "not [to] use the word 'first'—there is more than enough glory in the creation of the modern computer to satisfy all of the early pioneers, most of whom are no longer in a position to care anyway."[12] In the same address, Williams said: "If you add enough adjectives to a description you can always claim your own favorite. For example ENIAC is often claimed to be the 'first electronic, general purpose, large scale, digital computer' and you certainly have to add all those adjectives before you have a correct statement."[13] We endorse that sentiment, and we have no interest in perpetuating these squabbles by anointing ENIAC (or one of its rivals) as the singular "first computer." We are concerned instead with establishing what was new about ENIAC, and what was not. However, that does not mean that we accept the distinctions drawn by these adjectives as a full description of what was historically important about ENIAC. They are more useful for defining metaphorical rosettes to be pinned to the various machines than for understanding their actual historical legacies and the influence each machine exerted on other early computing projects.

ENIAC as an Obligatory Point of Passage

The consensus on ENIAC as the first electronic, general-purpose, large-scale digital computer defined its importance primarily as a milestone on the road leading to the "first stored-program computer." That journey was recently recounted as a "creation myth" by George Dyson in his book *Turing's Cathedral*, but in less romantic form it is also the basic structure of standard scholarly accounts.[14] For example, the narrative of Martin Campbell-Kelly and William Aspray's *Computer* takes the shape of an hourglass, with ENIAC as a narrow isthmus linking various areas of pre-World War II technological practice to the postwar world of electronic computing. This mirrors the diagram reproduced here as figure I.1, an influential diagram prepared by Arthur and Alice Burks in their classic paper on ENIAC. While arguing that the basic technology of the electronic digital computer was appropriated from Atanasoff, they nevertheless reinforced the centrality of ENIAC to the story of modern computing.

Earlier technologies were represented as contributions to the development of ENIAC, in which they were embedded. ENIAC, in turn, led to later generations of computer hardware. This made ENIAC what sociologists of scientific knowledge have called an "obligatory passage point" in historical narrative, a role it took quite literally in the long-running Information Age exhibit at the Smithsonian.[15] The first exhibit hall displayed a range of technologies for calculation, communication, and clerical work. As visitors progressed, the walls closed around them, forcing them through a narrow opening into a chamber holding as much of ENIAC as would fit in a small room while leaving space for a few mannequins and museum goers. Nearby monitors looped video clips in which the machine's creators discussed its role. History opened up again as the visitor emerged from ENIAC into the modern world of digital computing. The display dramatized ENIAC, almost literally, as the machine that gave birth to modern computing.

In such narratives, ENIAC fills much the same role as John the Baptist in the New Testament: that of an essential supporting player remembered primarily for heralding the coming of the central character. In the New Testament that is, of course, Jesus; in the history of computing it has traditionally been the "stored-program computer," the "modern computer," or, more precisely, the approach to computer design first documented in John von Neumann's "First Draft of a Report on the EDVAC" (1945) and almost universally adopted by the electronic computer projects of the late 1940s. EDVAC was planned as a successor to ENIAC, and so the ideas described in the First Draft were developed in collaboration with ENIAC's creators.

As we will show in chapter 6, the new approach to computer design was deeply influenced by ENIAC both as a tangible demonstration of what could be achieved with electronics and as a challenge to find much simpler and more efficient ways to control computations automatically. John the Baptist's head made a messy exit on a plate. ENIAC vanishes from most narratives shortly after being switched on for experimental use at the Moore School.

ENIAC as a Material Artifact

Much discussion of ENIAC has continued to be framed in terms of the extent to which it anticipated or influenced later computers. Insofar as the objective of any

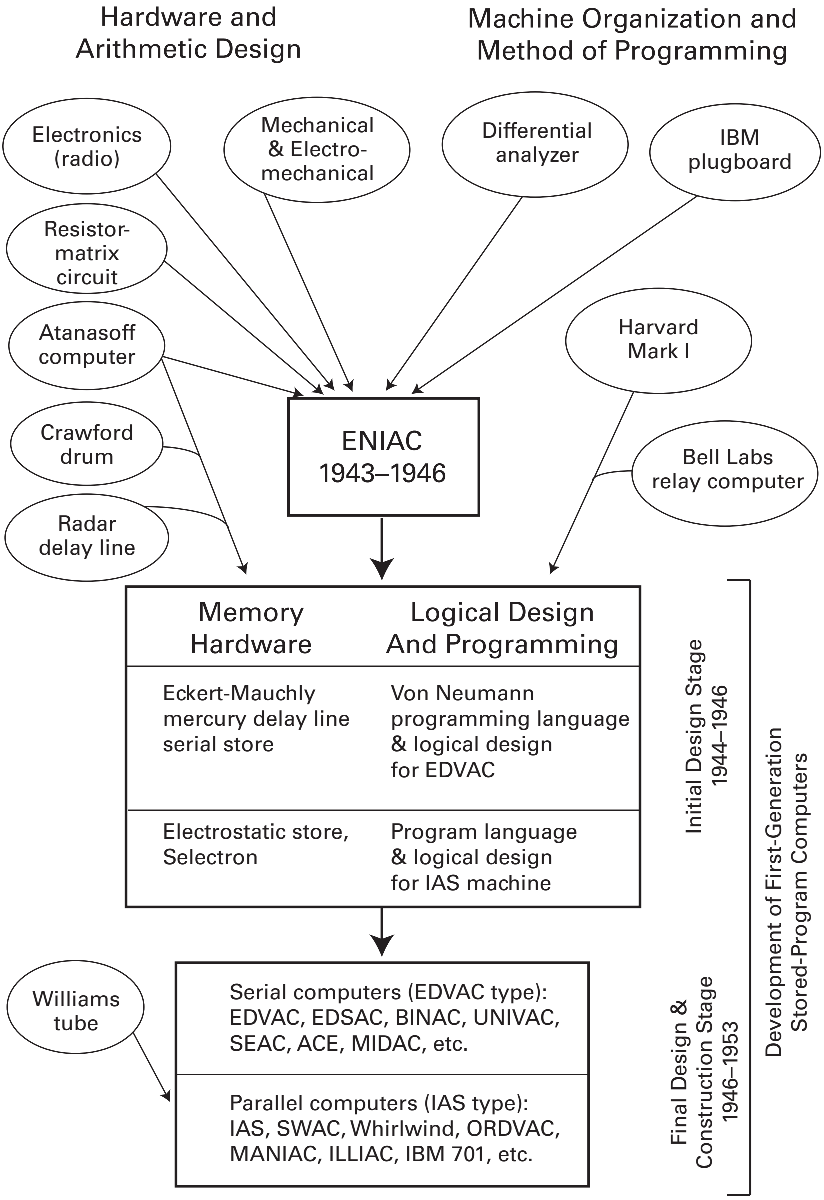

Figure I.1

Arthur and Alice Burks saw ENIAC as an obligatory passage point in the development of the modern computer. This diagram is from their article “The ENIAC: First General-Purpose Electronic Computer” (*Annals of the History of Computing* 3, no. 4, 1981: 310–389; ©1981 IEEE; reprinted, with permission, from *Annals of the History of Computing*).

overview history of computing is to explain the emergence of modern computer technology, that is entirely natural. ENIAC really was an indispensable link in a causal chain of innovation leading from hand-cranked calculating machines to modern supercomputers. Yet to remember ENIAC only as a stepping stone on the way to the digital world reduces it to a single moment, even if it boosts its significance. The actual machine and its career as a productive piece of scientific equipment disappear under the symbolic weight of world-changing importance.

One of our objectives is to use the rich archival evidence to re-engage with ENIAC as a physical artifact, following the recent revival of interest in "materiality" as a topic within science studies.[16] Historians have written about ENIAC's pioneering use of vacuum tubes, but not about the difficult challenges its creators faced in procuring and assembling its many other components (high-precision resistors, custom power supplies, even steel frames) in wartime. In chapter 3 we show that difficulties with these components, rather than vacuum tubes, caused the greatest concern as the computer's completion date slipped again and again during 1944 and 1945.

In focusing on ENIAC more as an idea than as a physical object, historians have naturally been more concerned with the engineers who designed the machine than with the dozens of "wiremen" who built it. We show that nearly all of the "wiremen" were women who, unlike the female ENIAC operators today lauded as the first computer programmers, have not been remembered by posterity. Blue-collar work has been less useful as a source of female role models, but without the toil of these forgotten women there would have been no ENIAC.

We reconstruct the rather shabby environment in which ENIAC was produced at the Moore School, documenting both a flood caused by the crumbling building that housed it and a fire sparked by flaws in the machine's cooling and safety systems. We also chart the difficulties caused by its move to its permanent home at the Ballistic Research Laboratory in Aberdeen, Maryland. The new space constructed for it at the BRL, which had air conditioning and a suspended ceiling, protected ENIAC and showcased its striking modernity.

ENIAC was a site of scientific spectacle.[17] Many delegations from companies and research groups were ushered inside the machine while it was still being built. Once it had been completed and installed at Aberdeen Proving Ground, work was often interrupted by parties of military visitors eager to witness it in action.

ENIAC was also a site of frequent frustration, to an extent that previous histories have not fully conveyed. In chapter 5 we show that ENIAC was only occasionally functional for more than a year after its arrival at Aberdeen. During four weeks in early 1948 a succession of failures, intermittent errors, and human errors meant that only the equivalent of one day of uninterrupted work was accomplished. This highlights the importance of maintenance work, another kind of labor previously neglected by historians of computing. Thanks to the efforts of the machine's operations and support teams in the next few years, ENIAC was eventually able to spend most of its time performing useful work, a transition we explore in chapter 10 along with the various modifications made to the machine over its operational life.

There is another sense in which ENIAC remained "in action" long after its first use in 1945. ENIAC was an exceptionally flexible piece of technology. Its hardware and its programming capabilities were repeatedly upgraded by its users. In 1948, after a long period of planning, ENIAC was reconfigured to use a programming method very similar to the method planned for the newer computers then under construction. We describe this process in chapter 7. It became the first computer to run a recognizably modern program. ENIAC had originally been a kind of modular kit from which a computer designed to solve a specific problem could be constructed by interconnecting wires and turning dials spread over several dozen bulky units. After its conversion, the wires and dials remained largely fixed in place until its retirement, implementing a number of generalized instructions. Programs were coded using these instructions and were stored on a set of read-only switchboards. This was a quite literal remaking of ENIAC around the new models of automatic computing to which it had given rise.

ENIAC as the Origin Point of Computer Programming

ENIAC's first six operators were hired in mid 1945. In a book titled *The Innovators* and subtitled *How a Group of Hackers, Geniuses, and Geeks Created the Digital Revolution*, Walter Isaacson demonstrates the extent to which their place in popular memory has come to overshadow that of the people who designed and built the machine. Isaacson writes dismissively of "the boys with their toys" who "thought that assembling the hardware was the most important job." In fact, he writes, "all the programmers who created the first general-purpose computer were women."[18] That baffling statement highlights both the extent to which the work of those women has come to overshadow the rest of ENIAC's story and a general lack of understanding of how "ENIAC programming" fits within the machine's overall story.

The women did play important roles in the success of ENIAC during the year it spent running problems at the Moore School, as did their less well-known successors who tended to ENIAC during its years in Aberdeen. We explore the full scope of their work, which included physically reconfiguring ENIAC, running cards through it and its auxiliary punched-card machines, and participating in the planning work we now think of as programming. Indeed, the fact that they are now celebrated exclusively as programmers rather than as operators is another sign of the technology world's disinclination to celebrate work seen as blue-collar. As Wendy Hui

Kyong Chun has noted, “reclaiming these women as the first programmers … glosses over the hierarchies … among operators, coders, and analysts.”[19]

Discussing this early work poses some linguistic and conceptual challenges. Though it has become common to speak of the work of configuring ENIAC to carry out the mathematical operations needed to tackle a particular problem as “programming” the computer, at the time such work was usually called “setting up” ENIAC for the problem. We likewise respect contemporary usage by calling the necessary configuration, which was documented on “set-up forms,” a “set-up” rather than a program.

We also illuminate several less familiar aspects of ENIAC’s contribution to the development of programming practice—for example, the establishment in 1947 of a team of programming contractors led by Jean Bartik (formerly Betty Jean Jennings), one of the initial operators. This is the first known example of programming being fully separated from other forms of work. Along with Adele Goldstine, this team contributed significantly to the conversion of ENIAC to the new programming mode that made it practicable to write complex programs for Monte Carlo simulation. This was the first modern computer code to be executed, and remarkably complete archival materials allow us to document (in chapter 8) its development from an initial mathematical plan through several generations of flow diagrams to a complete program listing. That process required the application of fundamental programming techniques such as loops, conditional branching, and arrays; it also required a well-developed methodology for the transformation of mathematical statements into programs.

ENIAC as a Site of Technical Analysis

One thing that sets this book apart from most histories of computing written by professionally trained historians in the past 20 years is its systematic engagement with aspects of the technical history of computing: the development of computer architecture, the evolution of programming practice, and the mutual shaping of mathematical practice against computational capabilities. We guide the reader through some fairly detailed examinations of computer designs, flow diagrams, and code. Those passages include an examination of the development of conditional control in chapter 2, a close reading of von Neumann’s “First Draft of a Report on the EDVAC” and its relationship to ENIAC in chapter 6, a discussion of the design process and programming techniques used to implement the first computer Monte Carlo simulation in chapter 8, and a comparison of ENIAC’s capabilities with those of other early computers in chapter 11. Further technical material, including various primary sources and an annotated version of the Monte Carlo code, is presented on the book’s companion website (www.EniacInAction.com).

We see this as part of a broader re-engagement of historians with the specifics of computer technology and the concerns of computer science. The history of science as a whole made a turn toward social and cultural analysis a generation ago, influenced by the emergence of science studies. Since then the wisdom of attempting to pry open the black boxes of technical knowledge and peer inside has been much debated.[20] Some scholars within science studies, such as Donald MacKenzie, have argued for the importance of understanding esoteric technical concepts well enough to demonstrate that even the most impersonal details of high technology are inseparable from social concerns. Others, such as Langdon Winner, have viewed the pursuit of technical detail as a distraction from social and political engagement.[21]

Within the history of computing, a relatively new and rather insecure subfield of the history of science and technology, the process of scholarly professionalization has been marked by a fairly uniform disengagement with technical detail in favor of stories about institutions, ideology, and occupations. Early historical work on computing, like early historical work on many other topics, was done by pioneers and other participants. They tended to produce detailed technical stories about particular computers, pioneering institutions, and the proper allocation of "firsts." Most of those entering the field as graduate students in history programs and science studies programs have lacked the technical background to appreciate or produce such stories, and have in any event sought instead to increase the scholarly respectability of the history of computing and their own potential employability by patterning their work on established models in better-developed historical fields. The development of the history of computing in a more scholarly direction has also been defined largely as a move away from technical history and technical details. Martin Campbell-Kelly, one of the field's most distinguished scholars, wrote a detailed exploration of the programming of early machines as his doctoral dissertation but later confessed to being embarrassed by that youthful indiscretion and turned to business history.[22] For a long while now, detailed examination of computer code or programming practice has been almost unknown in scholarly history of computing, seen at best as a guilty pleasure.

The change in methods was accompanied by a change in historical time frames. Scholars specializing in the history of computing paid relatively little attention to the machines of the 1940s, ENIAC included, from about 1990 to about 2010. Their stories had been well documented, and there were neglected topics of great importance in later eras. The publication in 2000 of the edited volume *The First Computers: History and Architecture* seemed for a while to represent the end of work on the topic rather than a new beginning.

In the past few years historians have begun to re-engage with the electronic computers of the 1940s and to bring some new questions and perspectives to their research. We have, in particular, grown more interested in questions of use and practice. This has reflected, in part, the incorporation of perspectives from this history and philosophy of mathematics in which technical exploration of the internal content of mathematical work has remained more prominent than in other areas of the history of science. Liesbeth de Mol and Maarten Bullynck have been particularly active in this area, examining ENIAC's use by Lehmer and its planned use by Haskell Curry.[23] ENIAC has begun to pop up as a supporting character in work on particular kinds of applied science. Most notably, its use for the first numerical weather simulations in 1950 and 1951 has been treated in some detail by Paul Edwards and Kristine C. Harper in two recent books.[24] As with Peter Galison's earlier discussion of ENIAC's role in early nuclear simulation, these narratives shift our understanding of ENIAC away from its traditional portrayal as one link in a chain running from primitive to modern computers and toward its work as an instrument for the creation of new kinds of scientific practice.[25] This parallels developments in the humanities outside existing work on history of computing, particularly attempts to establish fields such as "platform studies," "critical code studies," and "software studies."[26] The challenge is to re-surface from the sea of technical details clutching treasures that justify the dive.

This book is, in part, an experiment in the re-integration of technical detail into history influenced by the perspectives of science studies, labor history, institutional history, memory studies, and gender history. We see no essential boundary between these "social" perspectives and our more "technical" analysis. ENIAC's designers, builders, administrators, operators, programmers, and users were all, at the moment of their engagement with the machine, operating in both arenas, and we try to respect that when telling their stories.

ENIAC as an Object of Contested Historical Memory

ENIAC's history does not stop with its decommissioning in 1955. ENIAC has spent more time generating relics and parables than it ever did crunching numbers and punching cards. In chapter 12 we use some perspectives from the field of memory studies to explore its changing place in popular awareness during the intervening decades, from its role as a convenient yardstick to gauge the superiority of newer computers to its recent renown as a computer programmed by women.

It is not possible to fully separate this topic from the earlier narrative chapters. In attempting to reconstruct many aspects of ENIAC's history, such as the training of its operators, its public announcement, and the collaboration between its designers and John von Neumann to shape the next generation of computers, we found ourselves constantly grappling with contradictory statements made decades later by important participants. To some extent this may be blamed on the vagaries of human memory and on the mental processes by which people later make sense of their own actions by stitching them into coherent narratives. Many of the disagreements, however, are directly tied to the lengthy and unpleasant series of legal proceedings stemming from Eckert and Mauchly's June 1947 application to patent ENIAC, and with it the digital computer. They spent much more time arguing about ENIAC than they had spent building it. Less than three years after the first ENIAC contract was signed they had already left the University of Pennsylvania to try their luck as entrepreneurs. In contrast, 30 years went by between the start of work on ENIAC and the eventual invalidation of the patent in October of 1973.

From the 1950s on, many participants in the ENIAC project were repeatedly questioned, deposed, hired as consultants, or called to testify by lawyers representing various companies. They learned to speak cautiously and selectively about issues such as the influence, or lack thereof, of particular earlier projects on their own work. By the 1970s, sworn statements by ENIAC veterans enrolled on opposing sides were describing quite different versions of major events. The same people (among them Arthur Burks, Herman Goldstine, and Jean Bartik) went on to write extensively about ENIAC and its place in history.[27] Their accounts provide details and insights that are not available elsewhere, but they are also profoundly shaped by the positions of their authors in later battles. For example, Arthur Burks, who had designed much of ENIAC, later attempted to have himself added to the patent as a co-inventor so as to obtain license payments.[28] He and his wife Alice wrote the definitive technical history of ENIAC and wrote extensively about the capabilities and fate of Atanasoff's earlier computer.[29] They were careful researchers, and in places we rely on technical details from their work. We also include a number of quotations from Arthur's unfinished book on early computing. Yet their work—particularly Alice's book *Who Invented the Computer?*—is profoundly shaped by their experience in the lawsuit.[30] Her book is full of judgments against Mauchly's character and vituperative attacks on perceived enemies and is fixated on questions that no longer have consequence for anyone but the participants and their immediate family members.

At several points in the book we pause to engage with contradictory claims, exploring how narratives changed over time and, when possible, using archival evidence to evaluate the plausibility of particular stories. The incidents become case studies in the construction of historical memory. Many previous accounts uncritically accepted stories told in memoirs or oral history interviews, so we believe it is important to engage with these pervasive stories rather than simply ignoring them to substitute, without comment, our own narratives.

The reliance of historians and journalists on oral histories and memoirs, and in particular on a number of quotable anecdotes, has profoundly skewed dominant understanding of many aspects of ENIAC. For example, a great deal has been written about the process by which ENIAC was set up to demonstrate the calculation of shell trajectories for its public unveiling in February of 1946. Credit for that task has been vehemently disputed; however, participants and historians have tended to agree that work for the task began only a few weeks, or at most a few months, earlier, and that little attention had been given to ENIAC programming methods before the hiring of the first operators. This has given the job in question an almost mythic status as the first programming done for the first programmable computer.[31] All this has perpetuated a misconception that ENIAC was designed and engineered with no more than a vague appreciation of how it would be configured to carry out useful work.

Returning to the original archival materials enables us to present a more complex picture and to place the evolution of ENIAC programming within the broader context of the problem as a whole. In fact, planning for the calculation of shell trajectories was carried out very early in the project, starting in the autumn of 1943 with the production of configuration and timing diagrams. This took place in parallel with, and helped to shape, the detailed design of ENIAC's basic building block, the accumulator, and had been largely completed before significant design work took place on many of the machine's other units and long before the operators were hired. In this area, and in several others, our goal is not so much to provide the answers to controversial questions as to find different and better questions that steer us toward a deeper understanding of ENIAC's remarkable history.

Notes

Introduction

1. Douglas R. Hartree, *Calculating Machines: Recent and Prospective Developments and Their Impact on Mathematical Physics* (Cambridge University Press, 1947), 24 and 27.

2. Bruno Latour, *Science in Action: How to Follow Scientists and Engineers through Society* (Harvard University Press, 1987).

3. Peter Galison and Bruce Hevly, *Big Science: The Growth of Large-Scale Research* (Stanford University Press, 1992).

4. See, e.g., Nancy Beth Stern, *From ENIAC to Univac: An Appraisal of the Eckert-Mauchly Computers* (Digital Press, 1981), 16–23; Atsushi Akera, *Calculating a Natural World: Scientists, Engineers, and Computers During the Rise of U.S. Cold War Research* (MIT Press, 2007), chapters 1 and 2.

5. This perspective is sympathetic to that of Akera's book *Calculating a Natural World*, which situates ENIAC within an "ecology of knowledge."

6. During its most productive period, the early 1950s, ENIAC still had "25 per cent of its computing time devoted to artillery and bomb ballistics computation" (Harry L. Reed Jr., "Firing Table Computations on the Eniac," in *Proceedings of the 1952 ACM National Meeting (Pittsburgh)*, Association for Computing Machinery, 1952).

7. H. R. Keith, letter to R. E. Clement, October 27, 1952, Cuthbert C. Hurd Papers (CBI 95), Charles Babbage Institute.

8. Peter Galison, "Computer Simulation and the Trading Zone," in *The Disunity of Science: Boundaries, Contexts, and Power*, ed. Peter Galison and David J. Stump (Stanford University Press, 1996); Anne Fitzpatrick, *Igniting the Light Elements: The Los Alamos Thermonuclear Weapon Project, 1942–1952* (Los Alamos National Laboratory, 1999).

9. Recently, for example, in Alice Burks, *Who Invented the Computer? The Legal Battle That Changed Computing* (Prometheus Books, 2003) and Jane Smiley, *The Man Who Invented the Computer: The Biography of John Atanasoff, Digital Pioneer* (Doubleday, 2010).

10. Alice R. Burks and Arthur W. Burks, *The First Electronic Computer: The Atanasoff Story* (University of Michigan Press, 1989).

11. This distinction was introduced in an influential early description of Colossus as a "special-purpose program-controlled electronic digital computer" (Brian Randell, "The

Colossus," in *A History of Computing in the Twentieth Century*, ed. Nicholas Metropolis, Jack Howlett, and Gian-Carlo Rota, Academic Press, 1980). For more complete information on the machines in their use, see Jack Copeland, *Colossus: The First Electronic Computer* (Oxford University Press, 2006).

12. Michael R. Williams, "A Preview of Things to Come: Some Remarks on the First Generation of Computers," in *The First Computers: History and Architectures*, ed. Raúl Rojas and Ulf Hashagen (MIT Press, 2000).

13. Ibid.

14. George Dyson, *Turing's Cathedral: The Origins of the Digital Universe* (Pantheon Books, 2012); Martin Campbell-Kelly and William Aspray, *Computer: A History of the Information Machine* (Basic Books, 1996).

15. Michel Callon, "Some Elements of a Sociology of Translation: Domestication of the Scallops and the Fishermen of St Brieuc Bay," in *Power, Action and Belief: A New Sociology of Knowledge?*, ed. John Law (Routledge, 1986).

16. Trevor Pinch and Richard Swedberg, eds., *Living in a Material World* (MIT Press, 2008).

17. In part because the advancement of computer technology soon came to be associated with miniaturization, the use of computers as showpieces of scientific modernity has received less attention than more obviously monumental structures, such as the radio telescope. See Jon Agar, *Science and Spectacle: The Work of Jodrell Bank in Post-War British Culture* (Routledge, 1998).

18. Walter Isaacson, "Walter Isaacson on the Women of ENIAC," *Fortune,* October 6, 2014. Elsewhere in *The Innovators* (Simon & Schuster, 2014) Isaacson does discuss the work of Eckert, Mauchly, and Goldstine, so these remarks are more an odd rhetorical flourish than a systematic erasure of the role of ENIAC's actual designers, engineers, and builders.

19. Wendy Hui Kyong Chun, *Programmed Visions: Software and Memory* (MIT Press, 2011), 34.

20. Borrowing a term from electronic engineering, scholars characterized the inner workings of technological devices or scientific theories as "black boxes." In the original sense of that expression, "black boxing" a subsystem allowed engineers to focus on its documented inputs and outputs without having to worry about what was going on within.

21. Langdon Winner, "Upon Opening the Black Box and Finding It Empty: Social Constructivism and the Philosophy of Technology," *Science, Technology, & Human Values* 18, no. 3 (1993): 362–378.

22. Martin Campbell-Kelly, "The History of the History of Software," *IEEE Annals of the History of Computing* 29, no. 4 (2007): 40–51.

23. Maarten Bullynck and Liesbeth De Mol, "Setting-Up Early Computer Programs: D. H. Lehmer's ENIAC Computation," *Archive of Mathematical Logic* 49 (2010): 123–146; Liesbeth De Mol, Martin Carle, and Maarten Bullynck, "Haskell before Haskell: An Alternative Lesson in Practical Logics of the ENIAC," *Journal of Logic and Computation*, online preprint, 2013. The details of ENIAC set-ups are also explored in Brian J. Shelburne, "The ENIAC's 1949 Determination of π," *IEEE Annals of the History of Computing* 34, no. 3 (2012): 44–54.

24. Paul Edwards, *A Vast Machine: Computer Models, Climate Data, and the Politics of Global Warming* (MIT Press, 2010); Kristine C. Harper, *Weather by the Numbers: The Genesis of Modern Meteorology* (MIT Press, 2008).

25. Galison, "Computer Simulation and the Trading Zone."

26. The "platform studies" approach, championed in Nick Montfort and Ian Bogost, *Racing the Beam: The Atari Video Computer System* (MIT Press, 2009), is the approach most directly related to our work here. The "software studies" approach is explored in *Software Studies: A Lexicon*, ed. Matthew Fuller (MIT Press, 2008).

27. Herman H. Goldstine, *The Computer from Pascal to von Neumann* (Princeton University Press, 1972); Jean Jennings Bartik, *Pioneer Programmer: Jean Jennings Bartik and the Computer That Changed the World* (Truman State University Press, 2013); Arthur W. Burks and Alice R. Burks, "The ENIAC: First General-Purpose Electronic Computer," *Annals of the History of Computing* 3, no. 4 (1981): 310–399.

28. Burks' involvement in the ENIAC patent litigation of the 1960s and the 1970s is well documented in AWB-IUPUI. That collection includes probability trees in which he gamed out the financial payoff he expected to gain from his attempt to win recognition as a co-inventor of ENIAC.

29. Burks and Burks, "The ENIAC"; Burks and Burks, *The First Electronic Computer*.

30. Burks, *Who Invented the Computer?*

31. It is not altogether clear why this is the case, as it has long been known that ENIAC ran a highly complex calculation for Los Alamos weeks before the public launch.

Chapter 1

1. Earl R. Larson, Findings of Fact, Conclusions of Law, and Order for Judgment in *Honeywell Inc. v. Sperry Rand Corporation et al.* 180 USPQ 673, 1973 (available at ushistory.org).

2. Akera, *Calculating a Natural World*, 81.

3. Eckert's story is not as well documented as Mauchly's, but he comes vividly to life in Scott McCartney's book *ENIAC: The Triumphs and Tragedies of the World's First Computer* (Walker, 1999).

4. "1296. Eckert. T.I. (carbon) to Robert P. Mulhauf," in Diana H. Hook and Jeremy M. Norman, *Origins of Cyberspace: A Library on the History of Computing and Computer-Related Telecommunications* (Norman, 2002), 601.

5. McCartney, *ENIAC*, 43–45.

6. John W. Mauchly, "Amending the ENIAC Story," *Datamation* 25, no. 11 (1979): 217–219.

7. Goldstine, *The Computer*, 202.

8. According to Application for Federal Employment, July 1945 (in JWM-UP), Mauchly was appointed an assistant professor in September of 1941; however, Akera implies in *Calculating a Natural World* that there was an initial short-term contract.

9. David Alan Grier, *When Computers Were Human* (Princeton University Press, 2006), 134.

10. See table extracts reproduced in Harry Polachek, "Before the ENIAC," *IEEE Annals of the History of Computing* 19, no. 2 (1997): 25–30.

11. For contemporary treatments of exterior ballistics, see, for example, Ernest E. Herrmann, *Exterior Ballistics* (U.S. Naval Institute, 1935) or Gilbert Ames Bliss, *Mathematics for Exterior Ballistics* (Wiley, 1944). Interior ballistics, in contrast, studies the behavior of shells inside gun barrels.

12. Herrmann, *Exterior Ballistics*, v–vi; L. S. Dederick, "The Mathematics of Exterior Ballistic Computations," *American Mathematical Monthly* 47, no. 9 (1940): 628–634.

13. Vannevar Bush, "The Differential Analyzer: A New Machine for Solving Differential Equations," *Journal of the Franklin Institute* 212, no. 4 (1931): 447–488.

14. Irven Travis, OH 36: Oral History Interview by Nancy B. Stern, Charles Babbage Institute, October 21, 1977, 3.

15. J. G. Brainerd, "Genesis of the ENIAC," *Technology and Culture* 17, no. 3 (1976): 482–488.

16. Travis, OH 36: Oral History Interview by Nancy B. Stern, 3–4.

17. Gordon Barber, *Ballisticians in War and Peace, Volume 1: A History of the United States Army Ballistics Research Laboratories, 1914–1956* (Aberdeen Proving Ground), 17.

18. Travis, OH 36: Oral History Interview by Nancy B. Stern; Brainerd, "Genesis of the ENIAC," 484.

19. Barber, *Ballisticians in War and Peace*, 12–13.

20. Irven Travis, "Automatic Numerical Solution of Differential Equations," March 28, 1940, MSOD-UP, box 51; Burks and Burks, *The First Electronic Computer*, 182–184.

21. Goldstine, *The Computer*, 133.

22. Polachek, "Before the ENIAC."

23. Brainerd, "Genesis of the ENIAC," 484.

24. Polachek ("Before the ENIAC," 28) describes finding in one table errors of about 10 percent, caused by failure to convert between yards and meters.

25. Jonathan B. A. Bailey, "Mortars," in *The Oxford Companion to Military History*, ed. Richard Holmes et al. (Oxford University Press, 2001).

26. Whether the promised boost would be delivered is another question. According to Mitchell P. 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, no. 1, 1996: 17–24), "military tacticians have debated the value of printed ballistics tables especially as they were used in World War II. Field conditions rarely match the formal settings of a laboratory environment, and given the general patterns of combat during World War II, ballistics tables had a limited tactical value at best." Marcus and Akera attribute the production of the tables more to the efforts of mathematicians within the BRL to promote their relevance than to any particular demand from soldiers in combat.

27. Polachek, "Before the ENIAC."

28. Burks and Burks, *The First Electronic Computer*, 186–190.

29. John Mauchly, "The Use of High Speed Vacuum Tube Devices for Calculating," MSOD-UP, box 51 (PX-Electronic Computation (Mauchly)).

30. Goldstine, *The Computer*, 149.

31. Moore School of Electrical Engineering. "Report on an Electronic Difference* Analyzer," April 8, 1943, AWB-IUPUI. A footnote to the title explained the motivation for the new terminology. An April 2, 1943 version of this document marked as a "first draft" with the title "Report on an Electronic Diff.* Analyzer" is archived in MSOD-UP b51 (PX—Electronic Computation (Mauchly), 1942–1943).

32. Stern, *From ENIAC to Univac*, 18.

33. Section II.3 of the proposal explicitly compares the new machine with the differential analyzer.

34. Brainerd to Pender, April 26, 1943, MSOD-UP, box 51 (PX—Electronic Computation (Mauchly), 1942–1943).

35. Brainerd to Johnson, April 12, 1943, MSOD-UP, box 49 (PX-1 General).

36. Stern, *From ENIAC to Univac*, 18–23.

37. John Mauchly, "The Use of High Speed Vacuum Tube Devices for Calculating," MSOD-UP, box 51 (PX-Electronic Computation (Mauchly)). Akera (*Calculating a Natural World*, 86) interprets "step-by-step" as meaning "strictly sequential." However, the 1943 proposal made it clear that each step could contain many individual operations, some of which could be performed in parallel.

38. Travis, "Automatic Numerical Solution of Differential Equations." For a strong argument that Mauchly and Eckert were aware of Travis' earlier work, see Burks and Burks, *The First Electronic Computer*, 182–184.

39. John Mauchly, "The Use of High Speed Vacuum Tube Devices for Calculating," MSOD-UP, box 51 (PX-Electronic Computation (Mauchly)).

40. Moore School of Electrical Engineering. "Report on an Electronic Difference Analyzer," April 8, 1943, AWB-IUPUI.

41. Ibid., appendix C. As if to emphasize the general-purpose nature of the machine, appendix D contained a similar example of a program for a pair of rather different equations from interior ballistics.

42. Pender to MacLean, November 5, 1943, MSOD-UP, box 48 (PX-1).

43. "List of supplies and equipment needed for PX-1," May 6, 1943, MSOD-UP, box 48 (PX—drawings, pamphlets, estimates, misc.); Fetterolf to Brainerd, May 26, 1943; Fleitas to Brainerd, May 29, 1943, MSOD-UP, box 29 (PX-1 General).

44. Pender to Musser, June 7, 1943, MSOD-UP, box 51 (PX—Electronic Computation (Mauchly), 1942–1943).

45. Brainerd to MacLean, June 21, 1943, MSOD-UP, box 49 (PX-1 General).

46. Goldstine appears to have covered for Gillon himself at one point (Goldstine to Gillon, May 26, 1944, ETE-UP).

47. "War Research in the Moore School of Electrical Engineering," February 18, 1943, MSOD-UP, box 45 (Projects General, 1943).

48. Budget documents in MSOD-UP, box 48 (PX—Budgets, 1943).

49. "Check List for Things to be Done: Project PX," July 26, 1943, MSOD-UP, box 57 (Parts Lists, 1943–1944).

50. Fleitas to Brainerd, May 29, 1943, MSOD-UP, box 49 (PX-1 General, 1943).

51. John G. Brainerd, "Project PX—The ENIAC," *Pennsylvania Gazette* 44, no. 7 (1946): 16–17, at 32.

52. "Laboratory Notebook #4, Project PX #1. Issued to T. K. Sharpless by Isabelle Jay. 7/4/43", MSOBM-UP, box 2, serial no. 14 (Z14), p. 3.

53. Unlike the majority of later computers, ENIAC used the decimal rather than the binary number system.

54. "Report for Project PX: Positive Action Ring Counter (August 19, 1943)" and "Report for Project PX: The NCR Thyratron Counter," both in Arthur W. Burks, Laboratory Notebook, No. 1 (MSOBM-UP, box 1, serial no. 16).

55. "ENIAC Progress Report 31 December 1943," volume 1, MSOD-UP, box 1.

56. John Mauchly, "The Use of High Speed Vacuum Tube Devices for Calculating," MSOD-UP, box 51 (PX-Electronic Computation (Mauchly)).

57. "Report for Project PX, September 30, 1943, Accumulators and Transmitters," MSOD-UP, box 3 (Reports on Project PX).

58. Five handwritten pages numbered 1–5 pasted in as pages 94, 96, 88, 90, 92 of "PX Laboratory Notebook #1. Issued June 17, 1943 to Dr. A. W. Burks by Isabelle Jay," MSOBM-UP, box 2, serial no. 16 (Z16).

59. Kurt W. Beyer, *Grace Hopper and the Invention of the Information Age* (MIT Press, 2009), 55.

60. Hans Rademacher, "Mathematical Topics of Interest in PX: Part One—General Considerations" and "PX Report Number 14: Mathematical Topics of Interest in PX, Part Two: Summary of Articles Dealing with Rounding Off Errors," November 30, 1943, MSOD-UP, box 48 (PX-Computations, Rademacher, Etc.).

61. "Report for Project PX: Accumulators and Transmitters," September 30, 1943, MSOD-UP, box 3 (Reports on Project PX). For the manual calculations, see, for example, the 1943 calculation sheets preserved in MSOD-UP, box 48 (PX-Computations, Rademacher, Etc., 1943–1946), which recorded a maximum of eight significant figures.

62. "ENIAC Progress Report 31 December 1943," III, (3), (4).

63. Hans Rademacher, "On the Precision of a Certain Procedure of Numerical Integration," April 1944, MSOD-UP, box 48 (PX-Computations, Rademacher, Etc.).

64. "ENIAC Progress Report 31 December 1944," volume 1, MSOD-UP, box 1, III (3).

Chapter 2

1. Burks and Burks, "The ENIAC," 343.

2. For example, Eckert wrote of constraints imposed by "the limited time that conditions of war demanded" and suggested that use of "distributed control was dictated by the ease of building and getting it done in good time." J. Presper Eckert, "The ENIAC," in *A History of Computing in the Twentieth Century*, ed. N. Metropolis, J. Howlett, and Gian-Carlo Rota (Academic Press, 1980).

3. “Report for Project PX, September 30, 1943, Accumulators and Transmitters,” 3. Bound in “Reports on Project PX, Electronic Differential Analyzer, Moore School of Electrical Engineering, T. K. Sharpless,” MSOD-UP, box 3.

4. Sharpless, Z14 Notebook, p. 19.

5. Ibid., p. 24; Burks, Z16 Notebook, pp. 144–147.

6. Stern, *From ENIAC to Univac*, 47.

7. Burks, Notebook Z16. The diagram is pasted over p. 135. The next page holds notes of a meeting held on October 17, 1943.

8. Arthur W. Burks, unfinished book manuscript, chapter 5.

9. David Alan Grier, “The ENIAC, the Verb “to program” and the Emergence of Digital Computers,” *IEEE Annals of the History of Computing* 18, no. 1 (1996): 51–55.

10. In fact this idea of a computer as something that carries out a “sequence” of operations automatically is prevalent in early computing terminology, “sequence” having a meaning similar to that later given to “program.” IBM called the giant relay computer it built for Harvard University, often referred to as the Mark I, the “Automatic Sequence Controlled Calculator,” thus highlighting its ability to automatically execute a sequence of calculating operations. After falling out with Harvard, IBM built a bigger, better, and much more flexible rival to display at street level in its flagship New York building. The name of this “Selective Sequence Electronic Calculator” trumpeted another advance: the new machine could be configured to automatically select the appropriate sequence on the basis of the current state of its computation.

11. John Mauchly, “The Use of High Speed Vacuum Tube Devices for Calculating,” MSOD-UP, box 51 (PX-Electronic Computation (Mauchly)). Mauchly also uses the slight variant “programming device,” apparently with the same meaning. As we discussed in chapter 1, this device was to have a central coordinating role.

12. “Report on an Electronic Difference Analyzer,” April 8, 1943, appendixes A, C, and D.

13. Sharpless, Notebook Z14, p. 19, dated “11-6-43” and headed “Desc. of Program Unit.”

14. Sharpless, Notebook Z14, p. 144, dated “Nov. 20, 1943,” has the heading “Programming” for a block diagram of the circuits in the program unit of an accumulator.

15. The act of configuring what became ENIAC was already being called “set up” in the 1943 proposals, and this would appear to have evolved into the later usage of “set-up” as a noun to describe a particular configuration.

16. For example, “ENIAC Progress Report 31 December 1943” mentions the “24 different multiplication programs” that can be set up on the multiplication unit. This remained the basic sense of “program” in the literature on ENIAC: in 1946, Adele K. Goldstine, *A Report on the ENIAC Part I: Technical Description of the ENIAC, Volume I* (Moore School, University of Pennsylvania, 1946), p. I-21, stated that “the instructions given to a single program control are referred to as a ‘program’.” The title of appendix B of J. Presper Eckert et al., *Description of the ENIAC and Comments on Electronic Digital Machines. AMP Report 171.2R. Distributed by the Applied Mathematics Panel, National Defense Research Committee, November 30* (Moore School of Electrical Engineering, 1945), “Programming the ENIAC,” is one of the earliest uses of the word with something like its present meaning.

17. “ENIAC Progress Report 31 December 1943,” XIV (1–3).

18. These parameters, and the anti-aircraft application, are very similar to those chosen for the first known use of ENIAC to generate actual firing tables, in August of 1946. See “Deposition of Mrs. Genevieve Brown Hatch”, October 18, 1960, in GRS-DC, box 35 (Civil Action No, 105-146. Sperry Rand vs. Bell Labs. Deposition of Mrs. Genevieve Brown Hatch).

19. “PX-1-81: Setup of Exterior Ballistic Equations” in volume II of “ENIAC Progress Report 31 December 1943.”

20. The transfers shown between accumulators 2 and 3 in operation 2 in figure 2.2 take place in parallel with a multiplication (not visible in this excerpt) that takes nine addition times to complete, as is noted in the third column. Each row in the table corresponds to a mathematical operation, and parallelized operations have to be squeezed into the available space. By the end of 1944, the format had been tweaked so that each row represented one addition time, making the detailed timing considerations in the set-up easier to read.

21. “ENIAC Progress Report 31 December 1943,” IV (9).

22. “PX-1-82: Panel Diagram of the Electronic Numerical Integrator and Computer (Showing the Exterior Ballistics Equations Setup—Heun Method,” in volume II of “ENIAC Progress Report 31 December 1943,” GRS-DC.

23. Donald F. Hunt to Burks, November 16, 1970, AWB-IUPUI.

24. This reverses the layout used on the original sketch, and reflects the physical layout of ENIAC’s panels.

25. The most significant difference is that the setup form does not show which data lines are used to transfer numbers between units.

26. “ENIAC Progress Report 31 December 1943,” XIV (8).

27. “ENIAC Progress Report 30 June 1944,” MSOD-UP, box 1, p. 2 of preface.

28. This became standard practice in subsequent ENIAC programming, reflecting the importance that the team gave to checking the reliability of the machine.

29. “ENIAC Progress Report 31 December 1943,” IV (18).

30. “Meeting of April 21,” Z16 notebook, MSOBM-UP, box 1, serial no.16, pp. 244–255; also see Z14 notebook, MSOBM-UP, box 3, serial no. 14, pp. 60–61.

31. Z16 notebook, MSOBM-UP, box 1, serial no.16, p. 252. The register was introduced in the context of discussions about input and output capabilities, and its eighty-digit capacity precisely matched that of a punched card.

32. Arthur W. Burks, “Exhibit A: Contributions of Arthur W. Burks, Thomas Kite Sharpless, and Robert F. Shaw to the Design and Construction of the ENIAC,” paragraph A6, part of *Exhibits of Arthur W. Burks* in *Honeywell Inc. vs. Sperry Rand et al.*, AWB-IUPUI.

33. Notebook headed “Arthur W. Burks, PX April 28, 1944,” MSOBM-UP, box 2, serial no, 17 (Z17), pp. 15–16; “ENIAC Progress Report 30 June 1944,” IV-1. As finally constructed, ENIAC also included an initiating unit and comprised 30 units and 40 panels.

34. Marcus and Akera, “Exploring the Architecture of an Early Machine,” 21.

35. Howard A. Aiken and Grace M. Hopper, “The Automatic Sequence Controlled Calculator—I,” *Electrical Engineering* 65 (August–September 1946): 390.

36. Richard Bloch, “Programming Mark I,” in *Makin’ Numbers: Howard Aiken and the Computer*, ed. I. Bernard Cohen and Gregory W. Welch (MIT Press, 1999), 107.

37. “ENIAC Progress Report 31 December 1943,” XIV (8–9).

38. Ibid., XIV (9).

39. Ibid.

40. “ENIAC Progress Report 31 December 1943,” XII (2–3).

41. Ibid., XII (3).

42. Burks, unfinished book manuscript, chapter 5.

43. Undated manuscript pages in John Mauchly’s handwriting, HLU, box 7 (ENIAC: 1944 Notes Programmer). These documents make reference to Burks’ set-up, and also describe features of the master programmer. They can therefore be dated with confidence to the first half of 1944. The mid-year report noted (on p. IV-33) that some of the work described in the section on the master programmer had been done after the report’s date of June 30, 1944.

44. “ENIAC Progress Report 30 June 1944,” p. IV (40).

45. In fact, this diagram would not repeat the whole calculation as Mauchly claimed, because the stepper is not set back to its first stage after printing.

46. “ENIAC Progress Report 30 June 1944,” IV (40).

47. Mauchly’s plans also describe a rather mysterious “program coupling unit,” whose function remains obscure.

48. ENIAC Progress Report 30 June 1944, IV (33).

49. Ibid., IV (41).

50. This technique was documented in Goldstine, *A Report on the ENIAC*.

51. “ENIAC Progress Report 30 June 1944,” IV (40).

52. “ENIAC Progress Report 31 December 1944,” chapter 2 (11–13).

53. Goldstine, *A Report on the ENIAC*, (IV) 30.

54. “ENIAC Progress Report 30 June 1944,” IV (41).

55. Eckert et al., *Description of the ENIAC (AMP Report)*, appendix B.

56. Burks, unfinished book manuscript, appendix B.

Chapter 3

1. “Project PX #1, Notebook #8, issued Sept 30, 1943 to J. H. Davis,” MOSBM-UP, box 12, serial no. 2 (Z2), pp. 12–57.

2. “ENIAC Progress Report 30 June 1944,” I-5.

3. Brainerd to Goldstine, May 17, 1944, MSOD-UP, box 48 (PX-2 General Jan-Jun 1944).

4. “ENIAC Progress Report 30 June 1944,” II-1. See Davis’ notebook for accumulator tests.

5. Pender to Goldstine, July 3, 1944, GRS-DC, box 19 (PX—Project 1943–1946).

6. Burks and Burks, “The ENIAC,” 343 explain the mathematics of the two-accumulator test and highlight similarities between it and the set-up of a differential analyzer to solve the harmonic equation.

7. Sharpless, Z14 notebook, pp. 71–72 (June 27, 1944) and 73–75 (July 10, 1944).

8. Ibid., pp. 76–77 (July 18, 1944).

9. Arthur W. Burks, "Exhibit A: Contributions of Arthur W. Burks, Thomas Kite Sharpless, and Robert F. Shaw to the Design and Construction of the ENIAC," paragraph S15, part of *Exhibits of Arthur W. Burks* in *Honeywell Inc. vs. Sperry Rand et al.* in AWB-IUPUI.

10. McCartney, *ENIAC*, 79.

11. Numbers quoted for the number of joints in ENIAC vary by a factor of 50. The widely quoted figure of 5 million is currently endorsed by Wikipedia but, insofar as the total number of tubes, resistors, switches, and capacitors in ENIAC was approximately 105,000, implies that there were several dozen joints on each component. One witness in ENIAC patent trial stated that ENIAC had "in the order of one hundred thousand joints," which implies fewer joints than components. (Richard F. Clippinger, ENIAC Trial Testimony, September 22, 1971, ETR-UP, 8888.) The most plausible figure we found was an estimate of half a million joints given in one of the press releases for ENIAC's launch, "Physical Aspects, Operations of ENIAC are Described," War Department Bureau of Public Relations, HHG-APS, series 10, box 3, early February 1946, and later endorsed by Eckert himself in "Remarks by J. Presper Eckert, Dinner Marking 15th Anniversary of ENIAC," University of Pennsylvania, October 12, 1961, SRUV-HML, box 381 (Whitpain Dedication and ENIAC Dinner).

12. "PX-Project Laboratory Organization," May 4, 1944, MSOD-UP, box 48 (PX-2 General Jan-Jun 1944).

13. Arthur W. Burks, "Exhibit A: Contributions of Arthur W. Burks, Thomas Kite Sharpless, and Robert F. Shaw to the Design and Construction of the ENIAC, part of Exhibits of Arthur W. Burks in *Honeywell Inc. vs. Sperry Rand et al*," 1972, AWB-IUPUI, S7.

14. "Estimate of cost of six months (January 1 to June 30, 1944) continuation … ," December 7, 1943 and "Estimation of Cost: Completion of the ENIAC (Jun 1 to June 30, 1945)," both in MSOD-UP, box 49 (PX—Estimates).

15. We found the names of ENIAC workers in the detailed, tabulated accounting statements for "Project PX-2" in MSOD-UP, box 48 (MS-112). These list the full names of most employees, as do some of the monthly tabulations in "PX-2 Payrolls, 1944-1945" in the same archival box. By mid-1944, women made up a clear majority of those being paid to create ENIAC. Personnel records in MSOD, box 48 (MS-104) record earlier employment; pay rises and changes of status are logged in MSOD, box 49 (PX-2 Accounts 1944). Unlike ENIAC's operators, hired by the BRL the next year, these women have not been remembered by history, with the exception of Adele Goldstine ("Project Mathematician"). We can do little more than remember them here, as literal footnotes to the project's history. Let the record show that among the women who helped to design and build ENIAC during 1944 were Viola Andreoni, Martha Bobe, Lydia R. Bell, Vava Callison, Nellie T. Collett, O'Bera Darling, Helen Anna De Lacy, Jeanette M. Edelsack (draftswoman), Theresa Fraley, Gertrude E. Gilbert, Ann Gintis, Rita Golden, Margaret Henshaw, Jane Hodes, Virginia Humprey, Mary Ann Isreall, Dorothy F. Keller, Mary Knos, Alice T. Larsen, Alma Markward (assembler), Mary Martin, Anne D. McBride, Cathrine J. McCann (draftswoman), Rose McDonough, Mary E. McGrath, Mary McNetchell, Gertrude Moriarty, Anna Munson, Ann O'Neill, Violet Paige, Jane L. Pepper (draftswoman), Alice Pritchett, Ruth Ruch, Marjorie Santa Maria (draftswoman), Nancy Sellers, Eleanor Simone (technician), Carolyn Shearman, Dorothy K. Shisler, Frances Spurrier, Grace M. Warner, Evangeline E. Werley, Charlotte Widcamp, Sally Wilson, Diana Wrenn, and Isabelle Jay (secretary).

16. “List of supplies for beginning PX-1, April 24, 1943” and “List of supplies and equipment needed for PX-1, May 6, 1943.” In MSOD-UP, box 48 (PX—Drawings, Pamphlets, Estimates, Misc.).

17. Goldstine to Strachen, September 14, 1945, ETE-UP. In June of 1941 Signal Corps procurement centers in Chicago and San Francisco were merged into the Philadelphia operation, making it a national center for electronic supplies. By April of 1942, the Philadelphia depot handled more than 14 million pounds of incoming supplies each month and stockpiled more than 100,000 distinct items, according to George Raynor Thompson et al., *The Signal Corps: The Test (December 1941 to July 1943)* (Government Printing Office, 1957), 182.

18. Goldstine to Bennie, March 30, 1945, ETE-UP.

19. Brainerd to Bernbach Radio Corp, August 12, 1943, MSOD-UP, box 48 (PX-Manufacturers 1943). Two small strands of wire remain stapled to the file copy.

20. Various letters in MSOD-UP, box 48 (PX-2 General Jan-Jun 1944).

21. According to Eckert, ENIAC contained 70,000 of these, mostly “small one-half watt composition resistors.” J. Presper Eckert Jr., “Reliability of Parts,” in *The Moore School Lectures: Theory and Techniques for the Design of Electronic Digital Computers*, ed. Martin Campbell-Kelly and Michael R. Williams (MIT Press, 1985).

22. Goldstine to Gillon, August 21, 1944, ETE-UP. Pender’s relationship to IRC is discussed on page 20 of Travis, OH 36: Oral History Interview by Nancy B. Stern.

23. Goldstine to Bogert, July 9, 1945, ETE-UP.

24. Travis to Warshaw, MSOD-UP, box 52 (ENIAC Moving to Aberdeen).

25. Eckert, “Reliability of Parts.”

26. Akera, *Calculating a Natural World*, 100–101.

27. Ibid., 100. Randolph to Brainerd, August 5, 1944, MSOD-UP, box 48 (PX Tubes Manual).

28. A sketch of the test table can be found in Dais, Z2 Notebook, p. 100. For tests on individual tubes, see for example Sharpless Z14 Notebook, 86–95, recording work done in October of 1944.

29. Goldstine to Stibitz, August 12, 1944, ETE-UP.

30. Goldstine to Power, June 9, 1945, ETE-UP.

31. Goldstine to Pender, June 26, 1945, ETE-UP.

32. DuBarry to Greathread, September 15, 1945, GRS-DC, box 3 (Material Related to PX-Project) gives permission for Chandler and Flowers to visit in September and October of that year.

33. Stibitz to Weaver, November 6, 1943, MSOD-UP, box 49 (PX-1 General, 1943).

34. “Discussion of a Proposal by Dr. Stibitz for the Development of a Relay Differential Analyzer for Ballistics,” circa October 1943, MSOD-UP, box 49 (PX-1 General, 1943).

35. Stibitz to Weaver, November 6, 1943, MSOD-UP, box 49 (PX-1 General, 1943).

36. Goldstine to Stibitz, January 4, 1944, ETE-UP.

37. “Report of a Conference on Computing Devices,” February 1, 1944, ETE-UP.

38. Gillon to Brainerd, February 21, 1948, GRS-DC, box 3 (Material Related to PX-Project).

39. Goldstine to Stibitz, August 12, 1944, ETE-UP.

40. Von Neumann was also an important voice in these discussions. Von Neumann to Oppenheimer, August 1, 1944 (declassified Los Alamos document in possession of authors). Both he and Goldstine later helped the BRL define its requirements for the machine. Curry to Goldstine, September 12, 1945 and Goldstine to von Neumann, September 13, 1945, both in ETE-UP.

41. Goldstine to Gillon, September 2, 1944, ETE-UP.

42. Goldstine to Brainerd, February 1, 1944, ETE-UP.

43. William Aspray, *John von Neumann and the Origins of Modern Computing* (MIT Press, 1990), 30.

44. Goldstine to Brainerd, April 21, 1944, ETE-UP.

45. Goldstine to Quaintance, May 27, 1944, ETE-UP.

46. Stern, *From ENIAC to Univac*, 30.

47. Barnes to Pender, February 1, 1944, MSOD-UP, box 48 (PX-2 General Jan-Jun 1944).

48. Goldstine to Gillon, May 26, 1944, ETE-UP.

49. Ingersoll to Brainerd, June 8, 1944, MSOD-UP, box 48 (PX-2 General Jan-Jun 1944).

50. Goldstine to Pender, July 28, 1944, ETE-UP.

51. Goldstine to Gillon, September 2, 1944, ETE-UP.

52. Goldstine to Simon, August 11, 1944, ETE-UP.

53. Goldstine to Gillon, December 14, 1944, ETE-UP.

54. Campbell to Pender, February 20, 1945, MSOD-UP, box 49 (PX—Estimates).

55. Goldstine to von Neumann, May 15, 1945, ETE-UP.

56. Burks, "Contribution of Arthur W. Burks," S16. Burks had written the specifications for these units. Total power consumption is taken from War Department Bureau of Public Relations, "Physical Aspects, Operations of ENIAC."

57. Goldstine to Smith, February 12, 1945, MSOD-UP, box 48 (PX-Maguire Power Supplies).

58. Bill Yenne, *Tommy Gun: How General Thompson's Submachine Gun Wrote History* (Thomas Dunne Books, 2009).

59. Burks to Sarbacher, February 27, 1945, MSOD-UP, box 48 (PX-Maguire Power Supplies).

60. "Memorandum Concerning Meeting Between the Representatives of the University of Pennsylvania and Representatives of Maguire Industries, Inc.," April 7, 1945, MSOD-UP, box 48 (PX-Maguire Power Supplies). Maguire Industries' shift into radios and consumer products was eventually overshadowed by the political activity of its owner, Russell Maguire, who bankrolled the anti-Semitic tract *Iron Curtain Over America*.

61. Goldstine to Bogert, July 9, 1945, ETE-UP.

62. Burks, Z17 Notebook, pp. 57–62.

63. Brainerd to Goldstine et al., September 8, 1945, MSOD-UP, box 48 (PX-2 General Jul-Dec 1945).

64. Congress had defined ahead of time the procedure to be used when exercising the government's "convenience clause" at the end of the war, passing the Contract Settlement Act of 1944, Pub.L.No.78–395, 58 Stat. 649.

65. "Summary of W-670-ORD-4962," MSOD-UP, box 55a (ENIAC General, 1944–1945).

66. This is based on cost-of-living inflation measures, as determined by the Bureau of Labor Statistics CPI Inflation Calculator at http://www.bls.gov/data/inflation_calculator.htm. Since the economy was much smaller in the 1940s than it is today, this understates the importance of the investment even after adjusting for inflation.

67. Campbell to Pender, February 20, 1945, MSOD-UP, box 49 (PX—Estimates).

68. Lisa Todd is quoted discussing Holberton's responsibilities on page 15 of W. Barkley Fritz, "The Women of ENIAC," *IEEE Annals of the History of Computing* 18, no. 3 (1996): 13–28.

69. Jennings recalled that in late 1945 she and Snyder were assigned to work out a set-up to calculate a trajectory while Lichterman and Wescoff hand-computed exactly what ENIAC would compute. The results were used to verify the set-up and also later to help in debugging the physical set-up. Bartik, *Pioneer Programmer*, 85.

70. Fritz, "The Women of ENIAC." The work and training of the computers is reconstructed in Jennifer S. Light, "When Computers Were Women," *Technology and Culture* 40, no. 3 (1999): 455–483.

71. Bartik, *Pioneer Programmer*.

72. Fritz, "The Women of ENIAC," 15.

73. Ibid., 15–16. Herman Goldstine later claimed to have persuaded the Moore School to terminate its "arrangements with the elderly instructors" then training the computers, replacing them with three women including his own wife. Light ("When Computers Were Women," 467) showed that the three wives were in fact members of a larger group of three male and nine female instructors.

74. Grier, *When Computers Were Human*, 260.

75. She discussed her arrival in Philadelphia in Adele K. Goldstine, "Affidavit in Public Use Proceedings by IBM against the 1947 ENIAC Patent Application," 1956, HHG-APS, series 10, box 3.

76. Akera, *Calculating a Natural World*, 82.

77. Judy Green and Jeanne LaDuke, *Pioneering Women in American Mathematics: The Pre-1940s PhDs* (American Mathematical Society, 2008).

78. Herbert R. J. Grosch, *Computer: Bit Slices from a Life* (Third Millennium Books, 1991), 81.

79. Judy Green, "Film Review: Top Secret Rosies," *Notices of the AMS* 59, no. 2 (2012): 308–311.

80. David Alan Grier, "The Math Tables Project of the Work Projects Administration: The Reluctant Start of the Computing Era," *IEEE Annals of the History of Computing* 20, no. 3 (1998): 33–50. Much of the same material can be found in Grier, *When Computers Were Human*. The number of workers is taken from page 242 of the latter.

81. Janet Abbate, *Recoding Gender: Women's Changing Participation in Computing* (MIT Press, 2012), 18–19.

82. Bartik, *Pioneer Programmer*, 66–74.

83. JoAnne Yates, *Structuring the Information Age* (Johns Hopkins University Press, 2005). Lars Heide, *Punched-Card Systems and the Early Information Explosion, 1880–1945* (Johns Hopkins University Press, 2009).

84. L. J. Comrie, *The Hollerith and Powers Tabulating Machines* (Scientific Computing Service, 1933).

85. Wallace J. Eckert, *Punched Card Methods in Scientific Computation* (Thomas J. Watson Astronomical Computing Bureau, Columbia University, 1940).

86. Fritz, "The Women of ENIAC."

87. Goldstine, *The Computer*, 229–230. As well as enraging the women concerned, this statement also seems to discount the work of Burks, who figures more prominently than either of the Goldstines in archival materials concerning the design of ENIAC's control method and early work on the firing tables problem.

88. Goldstine, *A Report on the ENIAC*.

89. These affidavits, sworn in February of 1962, are preserved among the legal materials in HHG-APS, series 10, box 3.

90. Block diagrams were produced of all of ENIAC's units, giving a schematic view of their circuits. These are the diagrams the operators are usually assumed to be talking about, but the phrase was sometimes also applied to diagram formats specifically designed to representing ENIAC program structures, which would have had obvious relevance as programming tutorials. For example, Adele Goldstine wrote of the master programmer configuration diagrams as "block diagrams designed to summarize the way in which various program sequences of a problem are tied together." Goldstine, *A Report on the ENIAC*. Lehmer characterized what would later have been called a flow chart, showing decision points within a program, as "a block diagram of the ENIAC set up." D. H. Lehmer, "On the Converse of Fermat's Theorem II," *The American Mathematical Monthly* 56, no. 5 (1949): 300–309, at 302.

91. Bromberg to Goldstine, "Comments in Regard to Proposed Changes in Your Book Manuscript," April 5, 1971, HHG-HC box 1 (Correspondence, Apr 2, 1960–Apr 6, 1971).

92. Bartik, *Pioneer Programmer*, 75–76.

93. Fritz, "The Women of ENIAC."

94. Ibid., 21.

95. W. Barkley Fritz, "ENIAC—A Problem Solver," *IEEE Annals of the History of Computing* 16, no. 1 (1994): 25–45, at 28.

96. The United States tested a fission bomb, Ivy King, with a yield of about 0.5 megatons in 1952, but no further efforts were made in this direction as the first hydrogen bomb had already been successfully tested. Jeremy Bernstein, *Oppenheimer: Portrait of an Enigma* (Ivan R. Dee, 2004), 118.

97. Fitzpatrick, *Igniting the Light Elements*, 104.

98. Ibid., 175.

99. Ibid., 114.

100. Goldstine to Gillon, February 19, 1945, ETE-UP.

101. Fitzpatrick, *Igniting the Light Elements*, 115.

102. Goldstine to Metropolis and Frankel, August 23, 1945, ETE-UP.

103. Nicholas C. Metropolis, ENIAC Trial Testimony, December 13, 1971, ETR-UP, p. 14,454.

104. Jean J. Bartik and Frances E. (Betty) Snyder Holberton, "Oral History Interview with Henry S. Tropp, April 27, 1973," National Museum of American History, 1973 (http://amhistory.si.edu/archives/AC0196_bart730427.pdf), pp. 41–47 and 89.

105. Bartik, *Pioneer Programmer*, 84. Bartik implies an October date for the beginning of calculations on the Los Alamos problem, which is not consistent with primary sources.

106. Goldstine, *The Computer*, 226.

107. "ENIAC Service Log (1944-48)," AWB-IUPUI, January 1, 1946.

108. Ibid., December 9, 1945.

109. Ibid., December 26, 1945. The entry is signed "JWM."

110. Brainerd to Pender, November 14, 1945, MSOD-UP, box 48 (PX-2 General Jul-Dec 1945).

111. Brainerd to Pender, November 15, 1945, MSOD-UP, box 47 (Overhead Third Floor).

112. "ENIAC Service Log (1944-48)," February 7, 1946.

113. Bradbury to Barnes and Gillon, March 18, 1946, MSOD-UP, box 55a (Parts Supplies).

114. Nicholas C. Metropolis, Affidavit in *Sperry Rand et al. vs. Bell Telephone Laboratories*, January 3, 1962, HHG-APS, series 10, box 3.

115. Fitzpatrick, *Igniting the Light Elements*, 122–124.

116. Goldstine, *The Computer*, 231.

117. "Item 22904: Reclassification of the Project for Development of the Electronic Numerical Integrator and Computer," GRS-DC, box 3 (Material Related to PX-Project).

Chapter 4

1. Goldstine to Simon, December 12, 1945, ETE-UP.

2. "Press Arrangements for University of Pennsylvania E.N.I.A.C. Press Demonstration, 1 February 1946," HHG-APS, series 10, box 3.

3. "ENIAC Guide for Press Day, Feb 1, 1946," JWM-UP (Notes and Datasets: ENIAC Functions in Comparison to Other Computers, 1944–45).

4. "Dinner and Ceremonies Dedicating the Electronic Numerical Integrator and Computer," HHG-APS, series 10, box 3.

5. "Seating chart, ENIAC Dinner, Houston Hall, February 15, 1946," HHG-APS, series 10, box 3.

6. In fact the invitation, which gave a start time of 6:30 p.m., also noted that "informal demonstration and technical discussion" of ENIAC would take place throughout the preceding morning and afternoon, so that those interested could arrive "at whatever time on February 15 might be most convenient." "University of Pennsylvania Announcement re

Dinner and Ceremonies," HHG-APS, series 10, box 3. Eckert and Mauchly were asked to spend the day with ENIAC to answer any questions.

7. Goldstine, *The Computer*, 225–226.

8. Bartik, *Pioneer Programmer*, 98.

9. T. R Kennedy Jr., "Electronic Computer Flashes Answers, May Speed Engineering," *New York Times,* February 15, 1946.

10. The Moore School's concerns with Mauchly's slow progress on patent work are documented in Warren to Mauchly, November 2, 1945, AWB-IUPUI. The patent process was of understandable later interest to those involved, and many of the surviving collections of ENIAC material were formed from documents gathered in support of its litigation. We pay relatively little attention here to the reasons for the slow processing of the patent and the disputes between Eckert and Mauchly and the Moore School administrators. These issues have been argued in depth by others, and add little to the story of ENIAC's development and use.

11. Travis to Kessenich, November 18, 1946, MSOD-UP box 49 (Letters regarding reduction to practice).

12. This date for the acceptance of ENIAC by the U.S. government has been challenged by Goldstine, who argues that ENIAC was formally accepted by the Philadelphia Ordnance District on June 30, 1946. Goldstine, *The Computer*, 234.

13. "Affidavit of Adele K. Goldstine," May 1, 1956, HHG-APS, series 10, box 3.

14. "Affidavit of Mrs. Jean J. Bartik," February 17, 1962, HHG-APS, series 10, box 3, p. 3.

15. "Affidavit of Homer W. Spence," February 15, 1962, HHG-APS, series 10, box 3, p. 1.

16. John W. Mauchly, "The ENIAC," in *A History of Computing in the Twentieth Century*, ed. N. Metropolis, J. Howlett, and Gian-Carlo Rota (Academic Press, 1980), 541–550, 451–452.

17. Bartik, *Pioneer Programmer*, 90.

18. "Affidavit of Adele K. Goldstine," May 15, 1956, HHG-APS, series 10, box 3.

19. Goldstine, *The Computer*, 229–230. The other set-ups used at the demonstrations did not attract such passion. Even Bartik conceded that "the ENIAC women had nothing to do with the [press lunch on the] 1st, but I understand from people that were there that it was very unimpressive … they just had sines and cosines and things like that." Jean Bartik, "Oral History Interview with Gardner Hendrie, Oaklyn, New Jersey, July 1," Computer History Museum, 2008, accessed July 25, 2012 (http://archive.computerhistory.org/resources/text/Oral_History/Bartik_Jean/102658322.05.01.acc.pdf).

20. "Affidavit of Mrs. Jean J. Bartik."

21. Bartik, *Pioneer Programmer*, 80–81, 84–85, 91–92.

22. Bartik, "Hendrie Oral History, 2008," 28; Bartik, *Pioneer Programmer*, 95.

23. Bartik, "Hendrie Oral History, 2008," 30.

24. Thomas Haigh, "The Chromium-Plated Tabulator: Institutionalizing an Electronic Revolution, 1954–1958," *IEEE Annals of the History of Computing* 23, no. 4 (2001): 75–104.

25. "PX-1-82: Panel Diagram."

26. Program cards are first mentioned on page XIV (8) of "ENIAC Progress Report 31 December 1943." For the templates, see "ENIAC Progress Report 31 December 1944," page 23 and figure 4.

27. For example, Mauchly's comment on page 50 of "ENIAC Service Log (1944-48)" (December 18, 1945).

28. "PX-1-81: Setup of Exterior Ballistics Equations."

29. "ENIAC Progress Report 31 December 1944," 21–23. This example became a familiar tutorial resource, reappearing in several later reports and publications.

30. Ibid., 22.

31. Bartik, *Pioneer Programmer*, 91. Bartik claimed that the women had developed this diagramming technique, but archival evidence makes it clear that it predates their involvement with ENIAC.

32. Eckert et al., *Description of the ENIAC (AMP Report)*.

33. Goldstine, *A Report on the ENIAC*.

34. Jennings later insisted that Goldstine had no experience of ENIAC programming until after she had finished work on the manual, and claimed to have taught her how to program ENIAC when working with Taub in September of 1946. Bartik, *Pioneer Programmer*, 105. On page 11 she wrote: "*I* taught *Adele* to program the ENIAC. She knew the ENIAC technology because she had written the operator's manual, but she had not done a real program before I took her under my wing."

35. Three sheets provided to us by the Jean Jennings Bartik Museum headed "Compressible Laminar Boundary Layer. Zero-order Equations. Set up for integration procedure." We believe the handwriting to be Hartree's.

36. See, for example, Derrick Lehmer's set-up for the Riemann Zeta function, dating from 1947, which was documented using a hand-written flow diagram and two set-up tables preserved in MSOD-UP, box 9 (Riemann Zeta Fctn).

37. Eckert et al., *Description of the ENIAC (AMP Report)*, appendix B.

38. For example, Herman H. Goldstine and Adele K. Goldstine, "The Electronic Numerical Integrator and Computer (ENIAC)," *Mathematical Tables and Other Aids to Computation* 2, no. 15 (1946): 97–110.

39. "List of Problems That the ENIAC Has Been Used to Solve," in "Sperry Rand v. Bell Telephone Laboratories Civil Action No. 105-146: Defendant's Goldstine Exhibits," HHG-APS, series 10, box 3.

40. Charlotte Froese Fischer, *Douglas Rayner Hartree—His Life in Science and Computing* (World Scientific Publishing, 2003), 14.

41. Douglas R. Hartree, "Ballistic Calculations," *Nature* 106 (1920), September: 152–154. A broader overview of the British firing-table calculating effort of World War I, focused on the leading role of statistician Karl Pearson, can be found on pp. 126–133 of Grier, *When Computers Were Human*.

42. Fischer, *Douglas Rayner Hartree—His Life in Science and Computing*, 11–15.

43. Goldstine, *The Computer*, 246.

44. Hartree to Goldstine, January 19, 1946.

45. Goldstine, *The Computer*, 246.

46. Goldstine to Gillon, April 13, 1946. HHG-APS series 10, box 3.

47. Fischer, *Douglas Rayner Hartree—His Life in Science and Computing*, 109–113.

48. Cope and Hartree, "The Laminar Boundary Layer in Compressible Flow," plate 1, facing p. 4.

49. Douglas R. Hartree, *Calculating Instruments and Machines* (University of Illinois Press, 1949), 90.

50. Cope and Hartree, "The Laminar Boundary Layer in Compressible Flow," 56–63.

51. Cope and Hartree, "The Laminar Boundary Layer in Compressible Flow," 69.

52. "Compressible Laminary Boundary Layer: Calculation of Inputs for the Higher Order Equations," ENIAC-NARA, box 5, folder 2 (Hartree's Original Notes).

53. The entire equation, impressively complex, can be found on pp. 25–26 of Cope and Hartree, "The Laminar Boundary Layer in Compressible Flow."

54. Hartree, *Calculating Instruments and Machines*, 91.

55. Hartree, *Calculating Machines*.

56. J. Brillhart, "Derrick Henry Lehmer," *Acta Arithmetica* 62 (1992): 207–220; Bartik and Holberton, Oral History Interview with Henry S. Tropp, 68–69.

57. During 1946, Lehmer was recorded working with ENIAC only on April 22 and 23 (but probably continuing to April 26) and on May 13 and 14.

58. Lehmer, "On the Converse of Fermat's Theorem II," 301; Lehmer, "A History of the Sieve Process," in *A History of Computing in the Twentieth Century*, ed. N. Metropolis, J. Howlett, and Gian-Carlo Rota (Academic Press, 1980). This event is not recorded in the service log, but an archival list of applications run on ENIAC does note "computations completed during several holiday week ends," and it seems plausible that these might be less consistently logged. Hartree was using ENIAC around this time, so if Lehmer remembered the timing correctly then it must have been Hartree's set-up that was disrupted.

59. Bullynck and De Mol, "Setting-up early computer programs: D. H. Lehmer's ENIAC computation."

60. We have completed their set-up and verified it experimentally using an ENIAC simulator. With minor modifications, it works as intended and computes the results reported by Lehmer.

61. Lehmer, "A History of the Sieve Process," quotation on p. 451.

62. D. H. Lehmer, "On the Roots of the Riemann Zeta-function," *Acta Mathematica* 95 (1956): 291–298. We discuss the modifications in chapter 6.

63. Goldstine to Gillon, December 14, 1944, ETE-UP.

64. "Letter Order W 18-001 Ord 355 (P.O. 5-6016)" to Moore School from Ordnance Department, January 26, 1945, MSOD-UP, box 51 (Summary of Status of ENIAC Moving).

65. "Notes on Design and Construction for the AB-Installation," MSOD-UP, box 51 (AB—Installation—Dr. Brainerd, 1945).

66. Goldstine to Pender, April 13, 1945, MSOD-UP, box 51 (Summary of Status …).

67. The contract was "Contract W 18-001 Ord 335 (816)." An initial version was sent on May 8, but the Moore School objected to some terms and received a revised version on June

22 according to documents in MSOD-UP, box 51 (Summary of Status …). The value is taken from “Summary of Status MS111,” dated March 14, 1947.

68. Pender to Dubarry, February 5, 1945, MSOD-UP, box 51 (Summary of Status …). This created “a necessity for the Moore School to operate in a conservative manner even though this may result in higher costs to the Army” according to “Moore School Project AB Principles of Operation” in the same folder.

69. Sharpless to Research Division, October 26, 1946, MSOD-UP, box 51 (ENIAC Alterations, Repair of Fire Damage).

70. Travis to Murray, November 21, 1946 and Travis to Murray, January 21, 1947, both in MSOD-UP, box 51 (ENIAC Alterations, Repair of Fire Damage).

71. Lubkin to Simon, October 28, 1946, MSOD-UP, box 55a (ENIAC General, 1944–45).

72. Mauchly later faulted the Army for its rule that “any unattended hot electrical device required a guard for fire precautions, and this expense was not authorized. Whatever the reason for this rule, it was applied to the ENIAC, as a matter of routine it would seem. Whoever made such a rule probably made it for some good reason, but without knowing a thing about the ENIAC … . Here seems a clear case not only of stupid rules stupidly applied, but failing somewhere to transmit information vital” to ENIAC’s proper use. Mauchly, “The ENIAC,” 542–543.

73. “Government’s Order and Contractor’s Advice,” issued to the University of Pennsylvania by Aberdeen Proving Ground, December 5, 1946, MSOD-UP, box 51 (ENIAC Alterations, Repair of Fire Damage).

74. “Schedule ENIAC Move MS-111,” MSOD-UP, box 51 (ENIAC and EDVAC Progress Reports, 1946–1949).

75. Travis to Murray, November 8, 1946, MSOD-UP, box 51 (Summary of Status of ENIAC Moving).

76. Universal Insurance Company, “Special Floater Policy NO. V.S. 4098,” MSOD-UP, box 51 (Summary of Status …).

77. Scott Brothers to Trustees of the University of Pennsylvania, September 13, 1946, MSOD-UP, box 52 (ENIAC Moving (Frank T. Wilson Co., Scott Brothers)).

78. Stern, *From ENIAC to Univac*, 52.

79. Bartik, *Pioneer Programmer*, 88–89.

80. Ibid., 111.

Chapter 5

1. Goldstine, *The Computer*, 149.

2. Leslie E. Simon, Frank E. Grubbs, and Serge J. Zaroodny, *Robert Harrington Kent, 1886–1961: Biographical Memoir* (National Academy of Sciences, 1971).

3. Franz L. Alt, “Archaeology of Computers,” *Communications of the ACM* 15, no. 7 (1972): 693–694.

4. Barber, *Ballisticians in War and Peace*, 60.

5. Bartik, *Pioneer Programmer*, 79.

6. Barber, *Ballisticians in War and Peace*, 64.

7. Travis to Murray, "Modification of ENIAC Moving Contract," November 8, 1946, MSOD-UP, box 51 (Summary of Status of ENIAC Moving, 1944–1948).

8. Simon to Travis, December 18, 1946, MSOD-UP, box 51 (Summary of Status of ENIAC Moving, 1944–1948).

9. Simon to Pender, February 18, 1947, MSOD-UP, box 51 (Summary of Status of ENIAC Moving, 1944–1948).

10. "All panels are mounted in position allowing for change order of 27 February 1947 to permit the insertion of 2 extra panels for automatic program selector. This change order has been charged at $10,000 which will be added to moving contract." T. Kite Sharpless, "MS 111 Moving ENIAC: Progress Report 1 March 1947," MSOD-UP, box 51 (ENIAC and EDVAC Progress Reports). Eckert and Mauchly had proposed a "program selector" device in 1943—see chapter 1 above.

11. John Mauchly, "Card Control of Programming," August 11, 1945, UV-HML, box 7 (ENIAC 1944 Notes Programmer).

12. A. Goldstine, *Report on the ENIAC*, VII-22. Section 8.7 of the manual described an actual computation in which a similar situation arose.

13. If each of the twelve numerical switches on a row was set to 0 or 9, and the sign digits to P or M, then each of the fourteen switches would emit either 0 or 9 pulses when the row was stimulated by a program pulse.

14. Transcript of conversation among Travis, Dederick, and Lubkin, "late-March," 1947, MSOD-UP, box 51 (Summary of Status of ENIAC Moving, 1944–1948).

15. Reeves specialized in military electronics, and soon after the war was over it entered the market for analog computers with military contracts and commercial models. After arguing for Reeves a as reliable subcontractor, Lubkin briefly worked for the firm. James S. Small, *The Analogue Alternative: The Electronic Analogue Computer in Britain and the USA, 1930–1975* (Routledge, 2001), 110.

16. Fritz, "ENIAC—A Problem Solver," 29.

17. Ibid., 37–38. "ENIAC Log Book. Friday November 21, 1947," UV-HML, box 10 (Operations Log After 1947).

18. These details are taken largely from Fritz, "The Women of ENIAC."

19. Paul Ceruzzi, "Crossing the Divide: Architectural Issues and the Emergence of the Stored Program Computer, 1935–1955," *IEEE Annals of the History of Computing* 19, no. 1 (1997): 5–12. For an overview of the relay calculators of the 1940s, see Ceruzzi, "Relay Calculators," in *Computing Before Computers* (Iowa State University Press, 1990).

20. Wallace J. Eckert, "The IBM Pluggable Sequence Relay Calculator," *Mathematical Tables and Other Aids to Computation* 3, no. 23 (1948): 149–161.

21. Karl Kempf, *Electronic Computers Within the Ordnance Corps* (U.S. Army Ordnance Corps, 1961).

22. W. G. Andrews, "A Review of the Bell Laboratories' Digital Computer Developments," in *Review of Electronic Digital Computers: Joint AIEE-IRE Computer Conference (Dec. 10–12, 1951)* (American Institute of Electrical Engineers, 1952).

23. Fragments of program code could be split into tapes loaded onto different readers, giving a limited subroutine capability by transferring control from one to another at different points in the computation. Paper-tape drives could also be used for table lookup.

24. "Aberdeen Proving Ground Computers," *Digital Computer Newsletter* 7, no. 3 (1955): 1.

25. All quotations in this paragraph are from J. O. Harrison, John V. Holberton, and M. Lotkin, *Technical Note 104: Preparation of Problems for the BRL Calculating Machines* (Ballistic Research Laboratories, 1949).

26. Dorrit Hoffleit, "A Comparison of Various Computing Machines Used in the Reduction of Doppler Observations," *Mathematical Tables and Other Aids to Computation* 3, no. 25 (1949): 373–377, quotations from pp. 374 and 375.

27. Dorrit Hoffleit, "Oral History Interview with David DeVorkin, August 4, 1979," Niels Bohr Library and Archives, American Institute of Physics, College Park, Maryland.

28. Dorrit Hoffleit, *Misfortunes as Blessings in Disguise: The Story of My Life* (American Association of Variable Star Astronomers, 2002), 44–45.

29. Hoffleit, "Oral History Interview with David DeVorkin, August 4, 1979."

30. Hoffleit, "A Comparison of Various Computing Machines Used in the Reduction of Doppler Observations," 375.

31. Ibid., 376.

32. Andrews, "A Review of the Bell Laboratories' Digital Computer Developments."

33. Hoffleit, "A Comparison of Various Computing Machines Used in the Reduction of Doppler Observations," 376.

34. Fritz, "ENIAC—A Problem Solver." The BRL also used ENIAC to analyze visual data from camera stations, which likewise could be cross-referenced from several observation points to determine the actual position for the rocket being fired. Fritz cites several reports on this topic in section 1.2.22 of the appendix to the aforementioned article.

35. Barber, *Ballisticians in War and Peace*, 65–66, Boris Garfinkel, *BRL Technical Report 797: Least Square Determination of Position from Radio Doppler Data* (Aberdeen Proving Ground).

36. "ENIAC Service Log (1944–1948)", p. 163, entry dated "7/29/47".

37. Will Lissner, "Mechanical 'Brain' Has Its Troubles," *New York Times,* December 14, 1947. Lissner noted that the "balance" of the time (18 percent) was "believed to be wasted."

38. Mauchly, "The ENIAC," 542. Mauchly also claimed that Merwin and others from the Moore School "never reported that they had any difficulty getting similar performance" after the move to the BRL, which is hard to square with evidence in the operations log that Merwin was called to Aberdeen frequently to deal with intractable problems.

39. "Dr. Frank E. Grubbs," Ordnance Corps Hall of Fame, 2002, http://www.goordnance.army.mil/hof/2000/2002/grubbs.html.

40. Frank E. Grubbs, "A Quarter Century of Army Design of Experiments Conferences," Armyconference.org, 1980, http://www.armyconference.org/50YEARS/Documents/Typed%20Papers/DOE25Grubbs.pdf, 3.

41. Ibid., 4.

42. "Operations Log." Bierstein is mentioned as a newly arrived trainee on January 26, 1948. The assignment of personnel is noted in an entry dated March 15.

43. Ibid., February 25–27, 1948.

44. Ibid., March 1, 1948.

45. Ibid., March 2–3, 1948.

46. Ibid., March 4–12, 1948.

47. Ibid., March 15–17, 1948.

48. Ibid., March 18, 1948.

49. Ibid., March 19–22, 1948.

50. Hartree, *Calculating Instruments and Machines*, 119.

51. "Operations Log," March 23, 1948.

52. Ibid., March 23–24, 1948.

53. Frank E. Grubbs, "Sample Criteria for Testing Outlying Observations," *Annals of Mathematical Statistics* 21, no. 1 (1950): 27–58.

54. Frank E. Grubbs, "Procedures for Detecting Outlying Observations in Samples," *Technometrics* 11, no. 1 (1969): 1–21.

Chapter 6

1. See, for example, Ceruzzi, "Crossing the Divide: Architectural Issues and the Emergence of the Stored Program Computer, 1935–1955."

2. Modifying relay memory was slow because storing a number required movement of a physical switch. However, reads from relay memory could also be slow if (as on the IBM SSEC, which combined electronic logic with a fairly large relay memory) selecting the location from which to read itself involved the movement of relay switches.

3. The term "electronic speed" was used to describe the new pace of computation associated with ENIAC in various early reports, including Allen Rose, "Lightning Strikes Mathematics: Equations That Spell Progress Are Solved by Electronics," *Popular Science,* April 1946.

4. The 6SN7 devices used in the ring counter integrated two triodes into a single glass "envelope." This whole assemblage was usually considered to be one "tube," so the count of 28 given here is actually for envelopes. Sometimes the individual triodes within the envelope were considered "tubes" in their own right, which would yield a higher tube count.

5. In 1943 Eckert built the first successful delay line after introducing the idea of using mercury. See Eckert and Sharpless, "Final Report Under Contract OEMar 387," November 14, 1945, MSOD-UP, box 50 (Patent Correspondence, 1943–46). An earlier attempt to build a delay line using water and ethylene glycol had been made by William Shockley at MIT. See Peter Galison, *Image and Logic: A Material History of Microphysics* (University of Chicago Press, 1997), 505.

6. The delay-line memory was subsequently patented by Eckert and Mauchly. An early description appears in "Applications of the Transmission Line Register," circa August 1944, GRS-DC, box 3 (Material Related to PY Project).

7. Alice and Arthur Burks credited John Atanasoff with coming up with the basic idea of a regenerative memory and believed that this was one of the ideas Mauchly borrowed from him. The Atanasoff-Berry Computer used capacitors for its memory. See Burks and Burks, *The First Electronic Computer*.

8. "ENIAC Progress Report dated 31 December 1943," preface.

9. The canonical form of the anecdote is told by Goldstine on pp. 182–183 of *The Computer*.

10. For a general and surprisingly jovial account of von Neumann's life, see Norman McRae, *John von Neumann: The Scientific Genius Who Pioneered the Modern Computer, Game Theory, Nuclear Deterrence, and Much More* (Pantheon Books, 1992).

11. Aspray, *John von Neumann and the Origins of Modern Computing*, 26.

12. Ibid., 28–34.

13. When Warren Weaver received von Neumann's request for information on computing projects in January of 1944, he did not mention ENIAC. This is usually attributed to the unproven technology used, the experimental nature of the project, the low standing of the Moore School among the scientific elite, and the obscurity of Eckert and Mauchly within the mathematical community. See Aspray, *John von Neumann and the Origins of Modern Computing*, 35.

14. Goldstine to Gillon, August 21, 1944, ETE-UP.

15. Goldstine to Pender, July 28, 1944, ETE-UP.

16. Goldstine to Simon, August 11, 1944, ETE-UP.

17. On p. 185 of *The Computer*, Goldstine says that he showed von Neumann around ENIAC on August 7.

18. During the war von Neumann served as a consultant to numerous government organizations, "moving almost constantly from one project to the next." This included involvement with several divisions of the National Defense Research Committee and its successor, the Office of Scientific Research and Development, with Los Alamos, and with the Navy Bureau of Ordnance. However, his longest-standing consulting activity was with the Ballistic Research Laboratory, and insofar as he had been a founding member of its Scientific Advisor Committee one might expect him to have had a very good idea of how to frame a project to win support there. See Aspray, *John von Neumann and the Origins of Modern Computing*, 26–27.

19. Aspray, *John von Neumann and the Origins of Modern Computing*, 37.

20. Morrey to Simon, August 30, 1944, AWB-IUPUI.

21. Brainerd to Philadelphia Ordnance District, September 13, 1944, AWB-IUPUI.

22. Goldstine to Gillon, September 2, 1944, ETE-UP.

23. Ibid.

24. Brainerd to Gillon, September 13, 1944, ETE-UP.

25. Goldstine to Gillon, September 2, 1944, ETE-UP.

26. Goldstine to Gillon, August 21, 1944, ETE-UP.

27. Ibid.

28. Goldstine to Gillon, September 2, 1944, ETE-UP.

29. Goldstine to Gillon, December 14, 1944. Von Neumann's immersion in these circuits has often been overlooked by later commentators. For example, according to Scott McCartney (*ENIAC*, 128) "engineering structures … were outside von Neumann's area of expertise. The notion that von Neumann figured out better ways to wire up devices to manage electrical pulses is hard to figure."

30. Brainerd to Bogert, September 13, 1944, AWB-IUPUI. Only "Experimental work … on a small scale … in free time" was planned for 1944.

31. J. Presper Eckert, John W. Mauchly, and S. Reid Warren, PY Summary Report No. 1, March 31, 1945, GRS-DC, box 30 (Notebook Z-18, Harold Pender).

32. Goldstine to Power, February 19, 1945, and telegram from Goldstine to Gillon, December 14, 1944, both in ETE-UP.

33. "Notes of Meeting with Dr. von Neumann, March 14, 1945," "Notes on Meeting with Dr. von Neumann, March 23, 1945," "Notes on the First April Meeting with Dr. von Neumann (rough draft)," and "Notes on the Second April Meeting with Dr. von Neumann (rough draft)," all in AWB-IUPUI.

34. "The trunk system to connect the registers to the central equipment was discussed. At least three wires would be required, one for the input, one for the output, and one for control (i.e. the wire from the switch). This last wire could be dispensed with by using a recognition system, but the latter arrangement is more complicated than the former. The possibility of being able to connect both the control unit and the computor to tanks was discussed." "Notes of Meeting with Dr. von Neumann, March 14, 1945," AWB-IUPUI. According to later analysis by Burks, segregation was believed to have performance advantages. It would have been accomplished by setting controls to connect certain lines to a data "trunk" and the rest to a program trunk, rather than by physically separating tanks. Burks, unfinished book manuscript, appendix C.

35. Burks, unfinished book manuscript, chapter 7.

36. John von Neumann, "First Draft of a Report on the EDVAC," *IEEE Annals of the History of Computing* 15, no. 4 (1993): 27–75. Hereafter referred to as the First Draft.

37. Von Neumann to Curry, August 20, 1945, ETE-UP.

38. Von Neumann to Goldstine, February 12, 1945, AWB-IUPUI.

39. S. Reid Warren, "Notes on the Preparation of 'First Draft of a Report on the EDVAC' by John von Neumann. Prepared April 2, 1947," GRS-DC, box 3 (Material Related to the PY Project …).

40. J. Presper Eckert, John W. Mauchly, and S. Reid Warren, PY Summary Report No. 1, March 31, 1945, GRS-DC, box 30 (Notebook Z-18, Harold Pender).

41. Von Neumann to Goldstine, May 8, 1945, ETE-UP.

42. Goldstine to von Neumann, May 15, 1945, ETE-UP.

43. Burks' original carbon copy of the initial, internal version of the First Draft is preserved in AWB-IUPUI.

44. "Copies of von Neumann's report on Logical Analysis of EDVAC," June 24, 1945, GRS-DC, box 3 (Material Related to the PY Project …).

45. Curry to von Neumann, August 10, 1945, ETE-UP. Interestingly, Curry saw the arrangement of memory in temporal terms rather than spatial terms. He therefore proposed musical

metaphors, favoring “beat” as the “fundamental unit of time” and arguing for “measure” and “bar” rather than von Neumann’s “minor cycle” and “major cycle” to describe what would later be called “bits” and “words.” In view of the functioning of a delay-line memory, Curry’s might be a more intuitive metaphor than the idea that a datum is stored in a particular memory location.

46. Hartree to Goldstine, August 24, 1945, ETE-UP.

47. J. Presper Eckert, John W. Mauchly, and S. Reid Warren, PY Summary Report No. 1, March 31, 1945, GRS-DC, box 30 (Notebook Z-18, Harold Pender).

48. Burks, unfinished book manuscript, appendix C.

49. J. Presper Eckert Jr., John W. Mauchly, S. Reid Warren, PY Summary Report No. 2, July 10, 1945, GRS-DC, box 30 (Notebook Z-18, Harold Pender).

50. J. Presper Eckert and John W. Mauchly, Automatic High-Speed Computing: A Progress Report on the EDVAC (University of Pennsylvania, September 30, 1945).

51. Ibid., 3.

52. Burks, unfinished book manuscript, appendix C.

53. “Minutes of 1947 Patent Conference, Moore School of Electrical Engineering, University of Pennsylvania,” *Annals of the History of Computing* 7, no. 2 (1985): 100–116.

54. This critique is made, for example, by Stern (*From ENIAC to Univac: An Appraisal of the Eckert-Mauchly Computers*, 77-78) and by Campbell-Kelly and Aspray (*Computer*, 95).

55. C. Dianne Martin, “The Myth of the Awesome Thinking Machine,” *Communications of the ACM* 36, no. 4 (1993): 120–133.

56. Edmund C. Berkeley, *Giant Brains or Machines That Think* (Wiley, 1949).

57. Aspray, *John von Neumann and the Origins of Modern Computing*, 178–189.

58. Warren S. McCulloch and Walter Pitts, “A Logical Calculus of the Ideas Immanent in Nervous Activity,” *Bulletin of Mathematical Biophysics* 5 (1943): 115–133. For a useful discussion of this paper, see Gualtiero Piccinini, “The First Computational Theory of Mind and Brain: A Close Look at McCulloch and Pitts’s ‘Logical Calculus of Ideas Immanent in Nervous Activity,’” *Synthese* 141, no. 2, 2004: 175–215. We thank David Nofre for drawing our attention to Piccinini’s work.

59. Weaver to Brainerd, Dec 19, 1944, MSOD-UP, box 48 (PX-2 General Jul-Dec 1944).

60. Norbert Wiener, *Cybernetics, or Control and Communication in the Animal and the Machine* (Technology Press, 1948).

61. Steve Joshua Heims, *The Cybernetics Group* (MIT Press, 1991).

62. Thomas S. Kuhn, *The Structure of Scientific Revolutions*, second edition (University of Chicago Press, 1969).

63. Thomas S. Kuhn, “Second Thoughts on Paradigms,” in *The Essential Tension: Selected Studies in Scientific Tradition and Change* (University of Chicago Press, 1979).

64. John von Neumann, “The Principles of Large Scale Computing Machines (with an introduction by Michael R. Williams and a foreword by Nancy Stern),” *Annals of the History of Computing* 10, no. 4 (1988): 243–256, at 249.

65. Burks, unfinished book manuscript, chapter 7.

66. Antoine de Saint-Exupéry, *Wind, Sand and Stars* (Reynal and Hitchcock, 1939).

67. Goldstine to von Neumann, May 15, 1945, ETE-UP.

68. One can find quite different tube numbers quoted for many early computers, and in fact the exact number would have fluctuated over their operating lives as hardware was added and removed. According to Martin H. Weik (*BRL Report 971: A Survey of Domestic Digital Computing Systems*, Ballistic Research Laboratory, 1955), ENIAC then had 17,468 tubes, the IAS computer about 3,000, and SEAC 1,424. Simon Lavington, in *Early British Computers* (Digital Press, 1980), reports "800 thermionic valves" for the Pilot Ace (p. 44), 3,000 for EDSAC and, as of April 1949, 1,300 for the Manchester Mark 1 (p. 118). So effective was the new architecture in eliminating vacuum tubes that ENIAC's total was only ever exceeded by the immense AN/FSQ-7 computers that pushed the limits of 1950s computing technology for the military SAGE project.

69. Von Neumann, "First Draft of a Report on the EDVAC," section 5.6.

70. Ibid., section 2.5.

71. Burks, unfinished book manuscript, appendix C, section 1.

72. Burks later recalled Eckert objecting to his use of logic to describe part of the multiplier, and asking instead for practical diagrams of its actual circuits.

73. T. Kite Sharpless, "Von Neumann's Report on EDVAC—July 1945," April 2, 1947, GRS-DC, box 3 (Material Related to the PY Project …).

74. The list below has some overlap with the characteristics attributed to the "stored program concept" in Ceruzzi, "Crossing the Divide: Architectural Issues and the Emergence of the Stored Program Computer, 1935–1955," which shows that historians have invested "stored program" with a great deal more than the literal ability to store a program.

75. The order code specified in the report has been presented most clearly in M. D. Godfrey and D. F. Hendry, "The Computer as von Neumann Planned It," *IEEE Annals of the History of Computing* 15, no. 1 (1993): 11–21.

76. Von Neumann, "First Draft of a Report on the EDVAC," 37.

77. Ibid.

78. One of the ten arithmetic operations, *s*, would take a number from one or the other of the machine's arithmetic source registers, depending on the sign bit of the results of a previous arithmetic operation. Among other conditional operations, this could be used to set the address stored within an instruction to one of two possible values according to whether a particular condition was true or false. Von Neumann, "First Draft of a Report on the EDVAC," section 11.3.

79. Herman H. Goldstine and John von Neumann, "Planning and Coding Problems for an Electronic Computing Instrument. Part II, Volume 1," in *Papers of John von Neumann on Computing and Computer Theory*, ed. William Aspray and Arthur Burks (MIT Press, 1987), 154.

80. Eckert and Mauchly, Automatic High Speed Computing. This design choice was also made by Turing in his later plans for the ACE.

81. J. von Neumann, untitled manuscript 510.78/V89p, HHG-APS, series 5, box 1. This code is discussed in Donald E. Knuth, "Von Neumann's First Computer Program," *ACM Computing Surveys* 2, no. 4 (1970): 247–260.

82. For a logic-centered version of the story see Martin Davis, *Engines of Logic: Mathematicians and the Origin of the Computer* (Norton, 2001), 185.

83. An exception is the ACE, in which Turing followed von Neumann's original approach and implemented conditional branching by computing the desired unconditional branch instruction. Alan M. Turing, "Proposed Electronic Calculator (1945)," in *Alan Turing's Electronic Brain*, ed. B. Jack Copeland (Oxford University Press, 2012).

84. Arthur W. Burks, Herman Heine Goldstine, and John von Neumann, *Preliminary Discussion of the Logical Design of an Electronic Computing Instrument* (Institute for Advanced Studies, 1946).

Chapter 7

1. Martin Campbell-Kelly and Michael R. Williams, eds., *The Moore School Lectures: Theory and Techniques for Design of Electronic Digital Computers* (MIT Press, 1985).

2. Eckert, "A Preview of a Digital Computing Machine," in Ibid., quotations from pages 114 and 112.

3. John W. Mauchly, "Preparation of Problems for EDVAC-Type Machines," in *Proceedings of a Symposium on Large-Scale Digital Calculating Machinery, 7–10 January 1947*, ed. William Aspray (MIT Press, 1985) quotations from pages 203 and 204.

4. Engineering Research Associates, *High-Speed Computing Devices* (McGraw-Hill, 1950), 65.

5. Ibid., 62, 72.

6. Hartree, *Calculating Instruments and Machines*, 94. Hartree thus conceptualized the earliest EDVAC-type machines as a combination of the Harvard Mark I approach of programming via a machine-readable input medium with the new electronic logic units and a fast and large electronic memory. He did not, as later analysts would, see the external program storage of the Mark I as antithetical to the internal program storage of the new machines.

7. Hartree, *Calculating Instruments and Machines*, 88.

8. Maurice Wilkes, "What I Remember of the ENIAC," *IEEE Annals of the History of Computing* 28, no. 2 (2006): 30–31.

9. Nick Metropolis wrote that after his successful ENIAC runs in early 1948 "other Laboratory staff members made their pilgrimages to ENIAC to run Monte Carlo problems." Metropolis, "The Beginning of the Monte Carlo Method," *Los Alamos Science* 15 (1987): 122–130, at 128–129.

10. John von Neumann to Stanislaw Ulam, March 27, 1947, Stanislaw M. Ulam Papers, American Philosophical Society, Philadelphia (Series 1, von Neumann, John, #2).

11. Fritz, "ENIAC—A Problem Solver," 31.

12. The report on "Planning and Coding Problems for an Electronic Computing Instrument" was issued in installments during 1947 and 1948 and is reprinted in *Papers of John von Neumann on Computing and Computing Theory*, ed. William Aspray and Arthur Burks (MIT Press, 1987).

13. Eckert et al., *Description of the ENIAC (AMP Report)*, B-4.

14. A date of June 7 is given for Adele Goldstine's hiring in Goldstine, *The Computer*, 270. However one of his letters dated July 28 notes "Adele just received a duly signed and executed contract from Los Alamos. So she is now officially in business." Herman Goldstine to John von Neumann, July 28, 1947, JvN-LOC, box 4, folder 1. Klara von Neumann shifted from salary to hourly compensation at the end of August 1947, but it is not clear exactly when she was first hired. Kelly to Richtmyer, 28 Aug 1947, JvN-LOC, box 19, folder 7.

15. Goldstine, *A Report on the ENIAC*, section 7.4.

16. Richard F. Clippinger, "Oral History Interview with Richard R. Mertz, December 1, 1970," in Computer Oral Histories Collection. His claim has been repeated elsewhere, including Bartik, *Pioneer Programmer*.

17. Richard F. Clippinger, *A Logical Coding System Applied to the ENIAC (BRL Report No. 673)* (Aberdeen Proving Ground, 1948), 4.

18. Clippinger Trial Testimony, September 22, 1971, 8952–8968.

19. Eckert, "The ENIAC," 529.

20. Perhaps Clippinger contributed to some planned elaboration of the function-table control technique that led to or involved the still mysterious decision taken by the BRL very early in 1947 to order this new device.

21. The other members were Arthur Gehring, Ed Schlain, Kathe Jacobi, and Sally Spear. See Bartik, *Pioneer Programmer*, 115–116.

22. Bartik, "Hendrie Oral History, 2008."

23. JvN to R. H. Kent (BRL), June 13, 1947, JvN-LOC, box 4, folder 13.

24. Goldstine's travel records confirm visits to Aberdeen on August 29, 1947 and to the Moore School to visit Bartik's group on October 7 and October 17. A. Goldstine, "Travel Expense Bill," December 17, 1947, HHG-APS, series 7, box 1.

25. "Control Code for ENIAC," July 10, 1947, HHG-APS, series 10, box 3. We have made an electronic reproduction available at www.EniacInAction.com.

26. The design for the IAS computer was described in Burks, Goldstine, and von Neumann's highly influential technical report *Preliminary Discussion of the Logical Design of an Electronic Computing Instrument*.

27. Ballistic Research Laboratories, *Technical Note 141: Description and Use of the ENIAC Converter Code* (Aberdeen Proving Ground, 1949), 9. We have made an electronic reproduction available at www.EniacInAction.com. FTN stood for several different things in different revisions of the documentation. In this version it stood for "Function Table Numeric."

28. Herman H. Goldstine and John von Neumann, *Planning and Coding Problems for an Electronic Computing Instrument*, part II, volume I, section 7.

29. These steppers were among several new pieces of ENIAC hardware commissioned by the BRL. Design work was well advanced by summer 1947, as evidenced by blueprints PX-4–122 (June 10), PX-4–212 (July 2) and PX-4–215 (July 16)—all in UV-HML, box 17 (VII-5–4).

30. "60 Order Code, Nov 21—1947," HHG-HC, box 1, folder 5.

31. Bartik, *Pioneer Programmer*, 113–120.

32. "Problems 1947–1948," MSOD-UP, box 13 (Programming Group). Bartik, in *Pioneer Programmer*, can be read as claiming that the group was chartered explicitly to assist

Clippinger with the conversion work, but that is not consistent with archival evidence or with the timing of other developments.

33. An extensive collection of flow diagrams and programs written in the 60 order code can be found in MSOD-UP, box 9.

34. "Computation of an Exponential or Trigonometric Function on the ENIAC," MSOD-UP, box 9 (Set-up Sheets). Although the intention was presumably to write re-usable routines, program listings placed the code at a fixed position in the function tables. The subroutines would have been relocated by hand to include them within particular application, a chore aided somewhat by the use of symbolic addresses for the numerical data used within the subroutines.

35. "Testing ENIAC—60 Order Code," HHG-HC, box 1, folder 8.

36. Clippinger, *A Logical Coding System*.

37. Ibid. The flow diagram and the code tabulations are dated, respectively, March 2 and March 1, 1948.

38. Richard F. Clippinger, "Adaption of ENIAC to von Neumann's Coding Technique (Summary of Paper Delivered at the Meeting of the Association for Computing Machinery, Aberdeen, MD, Dec 11-12 1947)—Plaintiff's Trial Exhibit Number 6341," 1948, in ENIAC Trial Exhibits Master Collection (CBI 145), Charles Babbage Institute, University of Minnesota.

39. Will Lissner, "'Brain' Speeded Up, For War Problems! Electronic Computer Will Aid in Clearing Large Backlog in Weapon Research," *New York Times,* December 12, 1947. Before the current project, the most detailed discussion in recent decades of ENIAC's conversion, focusing particularly on the 60 order code, was in Hans Neukom, "The Second Life of ENIAC," *IEEE Annals of the History of Computing* 28, no. 2 (2006): 4–16, particularly its "Web extras" online technical supplement.

40. Von Neumann to Simon, February 5, 1948, HHG-APS, series 1, box 3.

41. Nick Metropolis and J. Worlton, "A Trilogy on Errors in the History of Computing," *Annals of the History of Computing* 2, no. 1 (1980): 49–59. Metropolis recalls having originated the idea of using the "converter" for decoding when "on a preliminary visit to the Aberdeen Proving Ground in Maryland" he "noticed a complete many-to-one decoder network nearing completion; it was intended to increase the capability of executing iterative loops in a program." We dated this trip to February 20 on the basis of the "Operations Log."

42. BRL staff members continued to work on the "60 order code" into March, so the decision by Metropolis and von Neumann to use the converter to enable the full range of two-digit codes unquestionably diverged from the BRL's established plans. However their idea may not have been as original as he later suggested. The concept of using the full range of two-digit codes predated their February 20 visit, as is shown by occasional log-book references from January 19, 1948 on to projected development of a "99 order code," apparently intended for use with the register memory. This would also have required use of the converter for decoding. Thus, although Metropolis was responsible for reworking plans for the initial reconfiguration to use the converter, he probably built upon existing plans to exploit the register (then expected to arrive around May of 1948).

43. Previous accounts have suggested that ENIAC was operated with the 60 order code for some time before the addition of the converter and the shift to the full 100 order code.

See, for example, Neukom, "The Second Life of ENIAC" and Fritz, "ENIAC—A Problem Solver."

44. See the set-ups for the basic sequence in "ENIAC—Details of code (16 Sep, 1948)" and "Detailed Programming of Orders" in ENIAC-NARA. These were the original binders documenting the ENIAC set-ups used during portions of its career at the BRL.

45. Ulam to von Neumann, May 12, 1948, JvN-LOC, box 7, folder 7.

46. Accounts differ on whether ENIAC was ever temporarily "reconverted" to run the ballistics calculations already programmed using its native mode. Clippinger ("Oral History Interview with Richard R. Mertz, December 1, 1970") later said that it was. However, we found no evidence of this in the log book during the period covered (through August 1949), and a February 1949 reconversion order from the BRL official Bernard Dimsdale was ignored by ENIAC staff after protests from John von Neumann that ENIAC's unique capabilities were crucial to the Atomic Energy Commission and would be jeopardized by a "double-changeover [that] can and probably will consume a great deal more time than one may optimistically estimate" (von Neumann to Kent, March 16, 1949, JvN-LOC, box 12, folder 3).

47. E.g. "Operations Log," April 2, 1948. The Monte Carlo programs used a "count" instruction for an application-specific purpose. This instruction did not appear in any of the order codes described in detail, providing evidence for the malleability of ENIAC's instruction set.

48. "Operations Log," April 14 and May 17, 1948.

49. Ballistic Research Laboratories, *Technical Note 141: Description and Use of the ENIAC Converter Code*; W. Barkley Fritz, *BRL Memorandum Report No 582: Description of the ENIAC Converter Code* (Ballistic Research Laboratory, 1951).

50. A twelve-digit number would not fit into a single accumulator. The three original function tables had 104 rows, but by 1951 ENIAC had acquired a fourth "high-speed function table," and the later converter codes allowed programmatic access to only 100 rows on each table.

51. J. O. Harrison, John V. Holberton, and M. Lotkin, Technical Note 104: Preparation of Problems for the BRL Calculating Machines (Ballistic Research Laboratories, 1949).

52. ENIAC worked with decimal numbers, which made the factors influencing the accuracy of its arithmetic easier for programmers to understand than with many of the binary machines that followed. However, it lacked floating-point capabilities, so called because they would delegate to the computer's hardware the task of tracking the implied position of the decimal point. For example, the gravitational constant is 667384 when expressed in metric units. The initial string of zeroes would fill all ten digits of an ENIAC accumulator. So the programmer would store the number as 667384 and make a note explaining that the results of any calculation involving it would need to be corrected appropriately. This helps to explain the importance of equipping the converter codes with an adequate supply of efficient shift instructions. A computer with floating-point capabilities would use its hardware to track the number of zeros following or preceding the digits actually stored, relieving the programmer of this chore.

53. "Since the ENIAC has relatively small sequencing and storage capacity but high speed of operation, it is usually desirable to carry out stepwise approximations on this machine by using low order approximations, small intervals, and many steps." Harrison, Holberton, and Lotkin, *TN104: Preparation of Problems*, 22.

Chapter 8

1. Galison, "Computer Simulation and the Trading Zone," 119.

2. Ibid., 120.

3. Michael S. Mahoney, "Software as Science—Science as Software," in *Mapping the History of Computing: Software Issues*, ed. Ulf Hashagen, Reinhard Keil-Slawik, and Arthur L. Norberg (Springer, 2002); Ulf Hashagen, "The Computation of Nature, Or: Does the Computer Drive Science and Technology?" in *The Nature of Computation. Logic, Algorithms, Applications*, ed. Paola Bonizzoni, Vasco Brattka, and Benedikt Löwe (Springer, 2013). The philosophical status of early Monte Carlo simulation was recently explored by Isaac Record in a PhD thesis titled Knowing Instruments: Design, Reliability, and Scientific Practice (University of Toronto, 2012).

4. The jump takes place at the bottom of page 130. Pages 130–135 then discuss the application of Monte Carlo methods to the Super, including ENIAC calculations performed in 1950.

5. Fitzpatrick, *Igniting the Light Elements*.

6. Donald MacKenzie, "The Influence of Los Alamos and Livermore National Laboratories on the Development of Supercomputing," *IEEE Annals of the History of Computing* 13, no. 2 (1991): 179–201.

7. Stanislaw M. Ulam, *Adventures of a Mathematician* (Scribner, 1976), 148.

8. Fitzpatrick, *Igniting the Light Elements*, 269.

9. Ulam, *Adventures of a Mathematician*, 196–201. Another firsthand account is given in Nick Metropolis, "The Beginning of the Monte Carlo Method," *Los Alamos Science,* Special Issue 1987. Several secondary treatments are cited in subsequent notes.

10. Aspray, *John von Neumann and the Origins of Modern Computing*, p. 111 and p. 288 (note 50). This public mention of Monte Carlo simulation seems to precede the well-known paper published as Stanislaw M. Ulam and John von Neumann, "On Combination of Stochastic and Deterministic Processes: Preliminary Report," *Bulletin of the American Mathematical Society* 53, no. 11 (1947): 1120.

11. Cuthbert C. Hurd, "A Note on Early Monte Carlo Computations and Scientific Meetings," *Annals of the History of Computing* 7, no. 2 (1985): 141–155. The report reproduced in that article is the source for much subsequent discussion of the computing plan, including Galison, "Computer Simulation and the Trading Zone," 129–130 and Record, "Knowing Instruments," 137–141.

12. Richtmyer's reply (also reprinted by Hurd in his 1995 article) points out that the "slower-down material" could be omitted for "systems of interest to us [at Los Alamos]"—that is, bombs. This suggestion was followed in the first version of the program, though the layer was eventually re-introduced to allow simulation of bombs with uranium hydride cores.

13. Von Neumann also proposed recoding the current zone number, to save having to derive this from the neutron's position.

14. R. D. Richtmyer, "Monte Carlo Methods: Talk given at the American Mathematical Society, April 24, 1959," SMU-APS, series 15 (Richtmyer, R.D. "Monte Carlo Methods"), 3.

15. Hurd, "A Note on Early Monte Carlo," 152 and 149.

16. Ibid., 152.

17. Dyson, *Turing's Cathedral*, 210.

18. J. von Neumann to Ulam, March 27, 1947, SMU-APS, Series 1, John von Neumann Folder 2.

19. "I am hoping to hear very soon from the 'Princeton Annex' some word of the first Monte Carlo." Mark to von Neumann, March 7, 1948, JvN-LOC, box 5, folder 13.

20. Dyson, *Turing's Cathedral*, 175–189 focuses on Klara von Neumann, as does Marina von Neumann Whitman, *The Martian's Daughter: A Memoir* (University of Michigan Press, 2012), 22–23, 38–39, 48–54.

21. A letter from Armand W. Kelley to Richtmyer dated August 28, 1947 confirms that the "necessary approvals have been obtained" for her employment by Los Alamos. JvN-LOC, box 19, folder 7. However, her informal involvement seems to have preceded this letter.

22. Klara von Neumann, "A Grasshopper in Very Tall Grass" (undated memoir), KvN-MvNW. Transcription by Marina von Neumann Whitman.

23. Ibid.

24. William Aspray and Arthur Burks, "Computer Programming and Flow Diagrams: Introduction," in *Papers of John von Neumann on Computing and Computer Theory*, ed. Aspray and Burks (MIT Press, 1987), 148.

25. The best-developed flow diagram produced for the first run measured approximately 24 inches by 18 inches in size, and is neatly written in the hand of Adele Goldstine with the heading "MONTE CARLO Flow Diagram 12/9/47," JvN-LOC, box 11, folder 7. We have made an electronic reproduction available from www.EniacInAction.com. A copy with two later handwritten annotations is in HHG-HC.

26. Ten manuscript pages numbered I, II.a—II.g, III. and IV, JvN-LOC, box 11, folder 8. An undated manuscript page on squared paper in JvN-LOC, box 11, folder 8, contains a plan of ENIAC's three function tables, labeled "FT I," "FT II," and "FT III." Common practice, followed in the Monte Carlo programs, was to use two tables to store the program code and the third "numeric function table" to hold data describing a particular physical situation.

27. Undated manuscript page headed "Refresh Random No." JvN-LOC, box 11, folder 8. John von Neumann was working personally on the methods for the generation of random numbers, so this might well have been written before or separately from the rest of the program.

28. Seven undated manuscript pages numbered 0 to 6 and a single page headed "Shifts," JvN-LOC, box 11, folder 8. The structure of the overview flow diagram on page 0 is reproduced in the shaded area of our figure 8.5. Additional diagrams on pages 1–3 represented the operation boxes and the connections between them in each of the twelve regions. Pages 4–6 contained detailed timing estimates for each box and region.

29. Two storage tables can be seen in our figure 8.1, one attached by a dashed line to the line between boxes 1* and 1.2* and one to the right of box 7*.

30. Von Neumann talks about the "square and take the middle digits" approach to generating pseudo-random numbers, and about testing the resulting distribution, in letters to A. S. Householder (February 3, 1948) and C. C. Hurd (December 3, 1948). See *John von Neumann: Selected Letters*, ed. Miklós Rédei (American Mathematical Society, 2005), 141–145.

31. This was another minor optimization—two of the four points at which new numbers had been generated were, by late 1947, modified to make use instead of particular digits within the number already generated.

32. The idea of a subroutine was familiar within the ENIAC team as early as 1945: "It is possible to have the main routine divided into sub-routines, in which case one stepper is used to feed another stepper, thus allowing the proper sub-routine to be chosen in the course of a regular routine." Eckert et al., *Description of the ENIAC (AMP Report)*, 3–7. This predates the earliest occurrence of the term recorded in the *Oxford English Dictionary*, a 1946 use by John von Neumann.

33. Martin Campbell-Kelly, "Programming the EDSAC: Early Programming Activity at the University of Cambridge," *Annals of the History of Computing* 2, no. 1 (1980): 7–36, at 17. Campbell-Kelly attributes the terminology used for the two types of subroutines to Douglas Hartree.

34. To be fair to Wheeler, who has been credited as the inventor of the closed subroutine, we should note that the Monte Carlo programs used a simple method to process the return address and relied on global variables as parameters and arguments. Campbell-Kelly shows that EDSAC practice soon moved beyond these particular mechanisms. Also, ENIAC's use of function-table memory eliminated the possibility of automatically relocating subroutines from a library, which was a major focus of early work on subroutines both by Goldstine and von Neumann (in the final installment of the "Planning and Coding … " reports cited earlier) and by the EDSAC team. The loss of this particular "first" takes little away from the substance of Wheeler's innovations.

35. The original simple sequence of operation box numbers was confused by alterations to the original diagram. Small insertions were placed in new boxes with decimal numbers, such as 20.1*. More radical changes led to new numbering sequences distinguished by overlining, or the use of the symbol °. For the second run, the boxes were renumbered sequentially, each functional region being allocated a block of ten numbers. As before, though, modifications soon led to the introduction of a variety of ad hoc symbols.

36. Hurd, "A Note on Early Monte Carlo," 155.

37. K. von Neumann, "Actual Running of the Monte Carlo Problems on the ENIAC," JvN-LOC, box 12, folder 6. An electronic reproduction of this document has been made available by the authors from www.EniacInAction.com.

38. For a comparison of alternative techniques of census taking, see E. Fermi with R. D. Richtmyer, "Note on Census-taking in Monte-Carlo Calculations" (LAMS-805, Series A), Los Alamos, July 11, 1948.

39. "Now the speed of a 1 MEV neutron is about 1.4×10^{-9} cm/sec and the mean free path between fissions is about 13 cm so the mean time between fissions is about 10^{-8} sec." Robert Serber, *The Los Alamos Primer (LA-1)* (Los Alamos National Laboratory Research Library, 1943), 2.

Chapter 9

1. For example, he wrote "Klari survived the Aberdeen expedition this time better than the last one" (letter to Ulam, November 18, 1948, JvN-LOC, box 7, folder 7). The word seems to

have been in common use in the von Neumanns' circle. Carson Mark also referred to a series of "rather major calculation expeditions" from Los Alamos to ENIAC in his testimony during the 1971 ENIAC patent trial ("Testimony: September 8, 1971," in volume 48 of *Honeywell vs. Sperry Rand*, 7504, ETR-UP). A meteorologist who worked with John von Neumann also wrote later of "ENIAC expeditions," the first of which was a "remarkable exploit" that "continued 24 hours a day for 33 days and nights." George W. Platzman, "The ENIAC Computations of 1950—Gateway to Numerical Weather Prediction," *Bulletin of the American Meteorological Society* 60, no. 4 (1979): 302–312, quotations from pp. 303 and 307.

2. Fitzpatrick, *Igniting the Light Elements*, 268.

3. Ibid.

4. Von Neumann to Bradbury, February 6, 1948, HHG-APS, series 1, box 3.

5. Von Neumann to Simon, February 5, 1948, HHG-APS, series 1, box 3; Simon to von Neumann, February 9, 1948, JvN-LOC, box 12, folder 3.

6. Von Neumann to Mark, March 13, 1948, JvN-LOC, box 5, folder 13.

7. "Operations Log."

8. The use of certain accumulators for the temporary storage of variables, the usage of the various digits of the random number ξ, the layout of the numeric function table and the constant transmitter registers, and a few numeric constants are listed on four undated manuscript pages on squared notepaper in JvN-LOC box 11, folder 8. The punched-card layout is described in the December 1947 flow diagram.

9. Richtmyer, 1959, "Monte Carlo Methods," p. 4.

10. "Receipt of Classified Materials," January 16, 1948, in JvN-LOC, box 19, folder 7.

11. "Operations Log," entries for April 1 and 2, 1948.

12. J. von Neumann to Ulam, May 11, 1948, SMU-APS, series 1 (John von Neumann Folder 2).

13. J. von Neumann to Ulam, May 14, 1948, SMU-APS, series 1 (John von Neumann Folder 2).

14. J. von Neumann to Ulam, May 11, 1948, SMU-APS, series 1 (John von Neumann Folder 2).

15. K. von Neumann to Ulam, June 12, 1948, ETE-UP.

16. JvN-LOC, box 12, folder 6, contains a seventeen-page manuscript titled "Actual Technique" and a typewritten transcription of the manuscript with insertions and corrections by John von Neumann numbered from x1 to x83 noted in the right margin. Eight larger passages of handwritten text on separate sheets are marked for insertion at various points. This document evolved into "Actual Running of the Monte Carlo Problems on the ENIAC," which will be discussed below.

17. Fitzpatrick, *Igniting the Light Elements*, 269.

18. J. von Neumann to Ulam, November 4, 1948, SMU-APS, series 1, box 29.

19. Three drafts of this report are held in JvN-LOC, box 12, folder 6. One of these is a manuscript in the hand of Klara von Neumann; the other two are typed versions of the same text. One typescript has been annotated and corrected all the way through, primarily by Klara von Neumann. Those corrections are incorporated into the version at

www.EniacInAction.com. Metropolis later wrote to Klara: “Here is your manuscript together with a rough typewritten copy … . The flow diagrams will definitely be finished on Monday and will be sent to you on that day.” Metropolis to K. von Neumann, September 23, 1949, JvN-LOC, box 19, folder 7.

20. K. von Neumann, “Actual Running … ” (typescript version), JvN-LOC, 5–6.

21. When a neutron reached a census time, ENIAC still interrupted the calculation of its course, resuming only when the card it had just punched was read back in. It appears it would have been possible simply to output a census card for analytical purposes, and then to proceed immediately to determine the fate of the neutron during the next census period. We conjecture that this was not done because it would have eliminated the possibility of doubling the neutron’s “weight” between census periods, described below.

22. The team assumed that running a simulation through 13 census cycles would be enough for the second run problems. K. von Neumann, “Actual Running … ” (typescript version), JvN-LOC, 13. This set a bound on the exponential growth in card numbers implicit in the doubling technique. Even so, 15,000–20,000 cards would be needed for each simulation.

23. J. von Neumann to Ulam, November 18, 1948, JvN-LOC, series 1 (John von Neumann Folder 1).

24. These documents are all found in JvN-LOC, box 11, folders 7 and 8. The program code has a title page reading “Card Diagram//FLOW DIAGRAM//Coding/Function Table III Values//Monte Carlo//Second Run.” Of these, only the Coding section remains. A note added by John von Neumann reads “Will be needed in LA in early January, but should then come to Princeton for reporting, etc. JvN.” An annotated version of this program code is included in Mark Priestley and Thomas Haigh, “Monte Carlo Second Run Code: Reconstruction and Analysis,” available from www.EniacInAction.com. The earlier draft flow diagram is a little messy, and can be distinguished from others in that folder by its lack of numbering. The later version is a mirror image negative that has corrupted somewhat over the years and is hard to read without image processing.

25. “Modular” in the sense that it appears to have been quite easy to restructure the program between the two runs by splitting one region into two, and reordering several of the regions, for example.

26. Some instructions included addresses or data as well as a two-digit operation code, but most did not. The program for the second run used approximately 2.5 digits per instruction.

27. Teller’s campaign for hydride weapons is discussed in Gregg Herken, *Brotherhood of the Bomb: The Tangled Lives and Loyalties of Robert Oppenheimer, Ernest Lawrence, and Edward Teller* (Holt, 2003).

28. J. von Neumann to K. von Neumann, December 7, 1948, KvN-MvNW.

29. J. von Neumann to K. von Neumann, December 13, 1948, KvN-MvNW.

30. Ulam to J. von Neumann, February 7, 1949, JvN-LOC, box 7, folder 7.

31. LAMS-868, “Progress Report T Division: 20 January 1949–20 February 1949,” March 16, 1949, quoted in Fitzpatrick, *Igniting the Light Elements*, 269. The original report remains classified.

32. Maria Mayer, “Report on a Monte Carlo Calculation Performed with the ENIAC,” in *Monte Carlo Method*, ed. Alston S. Householder (National Bureau of Standards, 1951).

33. J. von Neumann to K. von Neumann, December 7 and December 13, 1948, both in KvN-MvNW. The word "pedaling" appears several times in the ENIAC Operations Log as work is starting in a particular calculation. We believe that it meant stepping through a program slowly for diagnostic purposes.

34. J. von Neumann to K. von Neumann, March 27, 1949, KvN-MvNW.

35. Ulam to J. von Neumann, May 16, 1949, JvN-LOC, box 7, folder 7.

36. K. von Neumann to Mayer, April 8, 1949, KvN-MvNW.

37. J. von Neumann to K. von Neumann, March 27, 1949, KvN-MvNW.

38. K. von Neumann to Dederick, May 16, 1949, JvN-LOC, box 19, folder 7.

39. We have located in JvN-LOC what appears to be a flow diagram for this run, which followed John von Neumann's advice in sticking with the established time-based census method. The diagram is undated and untitled but is neatly stenciled, has nodes numbered 1 to 98, and includes a penciled note reading "The revised diagram will follow when completed in all its beauty. J." As well as a number of general refinements it includes a representation of the code for scattering in "light materials" missing from the flow diagrams for the second run but present as an optional code block within the corresponding program. This fits with the established need to repeat the hydride calculations performed during the second run, and an observation by Fitzpatrick that the 1949 calculations concerned, at least in part, a bomb design code-named Elmer with a hydride core. Fitzpatrick, *Igniting the Light Elements*, 269.

40. "Operations Log."

41. Letter of June 28, quoted in Dyson, *Turing's Cathedral*, 198.

42. J. von Neumann to Ulam, November 4, 1948, SMU-APS, series 1 (John von Neumann Folder 2).

43. Fitzpatrick, *Igniting the Light Elements*, 143.

44. J. von Neumann to Ulam, May 23, 1949, SMU-APS, series 1 (John von Neumann Folder 3).

45. Fitzpatrick, *Igniting the Light Elements*, 143–149, quotation from p. 149.

46. J. von Neumann to Teller, April 1, 1950, JvN-LOC, box 7, folder 4.

47. J. von Neumann to Mark, April 19, 1950, JvN-LOC, box 5, folder 13.

48. Evans to K. von Neumann, February 8, 1952, JvN-LOC, box 19, folder 7.

49. As reconstructed for the fiftieth-anniversary celebration, the Baby's first program consisted of 19 instruction lines, read no input (understandable as switches were the only input device), and ran for 52 minutes with the intention of giving the hardware (particularly the novel memory unit) a thorough workout. (See http://www.computer50.org/mark1/firstprog.html.) The programs run at the EDSAC's inaugural demonstration on June 22, 1949, which printed tables of squares and prime numbers, were longer, consisting of 92 and 76 instructions respectively, much of which was code to print the results in an attractive format. W. Renwick, "The E.D.S.A.C. Demonstration," in *The Early British Computer Conferences*, ed. M. R. Williams and M. Campbell-Kelly (MIT Press, 1989), 21–26.

50. One exception is Crispin Rope, "ENIAC as a Stored-Program Computer: A New Look at the Old Records," *IEEE Annals of the History of Computing* 29, no. 4 (2007): 82–87.

51. Galison, "Computer Simulation and the Trading Zone," 120.

52. The von Neumanns and the Goldstines were married before engaging with ENIAC. Others found love within the ENIAC teams at the Moore School and at the Ballistic Research Lab. Within a few years, the Holbertons, the Spences, the Reitwiesners, and the Mauchlys (John Mauchly having remarried after the sudden death of his first wife) were all brought together by their shared connection to the machine. Light ("When Computers Were Women," note 37) discusses this and also mentions other examples of scientific couples during the era.

Chapter 10

1. "Operations Log," May 17 and 18, 1948.

2. "Description of Orders for Coding ENIAC Problems," July 6, 1948, HHG-HC, box 1.

3. "Operations Log," July 12–14, 1948.

4. Ibid., July 22 and August 5, 1948. Results from Clippinger's calculations were published in Richard Clippinger and N. Gerber, *BRL Report No. 719: Supersonic Flow Over Bodies of Revolution (With Special Reference to High Speed Computing)* (Ballistic Research Laboratory, 1950).

5. "ENIAC Details of CODE In effect on 16 September, 1948." The new instruction set allowed some use of the master programmer to control fixed loops, and contained alternate delay and halt instructions.

6. "Operations Log," October 9, 1948.

7. Bergin, ed., *50 Years of Army Computing*, 35.

8. Melvin Wrublewski, "ENIAC Operating Experience," *Ordnance Computer Newsletter* 1, no. 2 (1954): 9–11 (in HHG-APS, series 4, box 1).

9. Clippinger, *A Logical Coding System*.

10. The Operations Log for April 20, 1948 records "Talked with Clippinger and Dimsdale about new developments in the new code designed for use with the register." The planned instruction set was described in B. Dimsdale and R. F. Clippinger, "The Register Code for the ENIAC," in *BRL Technical Note 30: Report on the Third Annual Meeting of the Association for Computing Machinery* (Ballistic Research Laboratory, 1949): 4–7, 11–14. The ACM did not yet produce conference proceedings, so this was a summary prepared by members of the BRL staff in attendance.

11. EDVAC had acquired short tanks by September of 1945, perhaps in response to von Neumann's experiments in coding Eckert and Mauchly, Automatic High-Speed Computing. Turing employed the same strategy in his ACE report, written toward the end of the year.

12. Nancy Stern, "The BINAC: A Case Study in the History of Technology," *Annals of the History of Computing* 1, no. 1 (1979): 9–20.

13. "Operations Log," January 10 and January 20, 1949.

14. Ibid., June 29, 1949.

15. G. W. Reitwiesner, "Stand-by Plan for Operation of the ENIAC," April 1, 1949, ENIAC-NARA, box 2, folder 3. This proposed new designs to provide storage more efficiently than the existing accumulators.

16. Homer W. Spence, "Operating Time and Factors Affecting It, of the ENIAC, EDVAC, and ORDVAC During 1952," ENIAC-NARA, box 2, folder 10.

17. A total of 87 problems are known to have run on ENIAC. We believe that it tackled about a dozen of them in its original mode. Thus, it appears that 75 problems were tackled in the first four years after conversion to the modern code paradigm.

18. Kempf, *Electronic Computers Within the Ordnance Corps*, 34.

19. Akera, *Calculating a Natural World*, 100–102.

20. Representatives of MIT's Whirlwind project paid great attention to the manufacturing standards used on the 7AK7 to verify its suitability for their new computer as a long life tube. Brown et al. to Forrester, "Investigation of 7AK7 Processing, Emporia, PA," March 16, 1948, in Project Whirlwind Reports, MIT Libraries. Online at http://dome.mit.edu/handle/1721.3/38986.

21. Richard F. Clippinger, ENIAC Trial Testimony, September 22, 1971, ETR-UP, p. 8888.

22. "Aberdeen Proving Ground Computers: The ENIAC," *Digital Computer Newsletter* 3, no. 1 (1951): 2.

23. "Aberdeen Proving Ground Computers," *Digital Computer Newsletter* 3, no. 3 (1951): 2.

24. "Operations Log," December 13, 1948.

25. Bergin, *50 Years of Army Computing*, 154–155.

26. Ibid., 45.

27. Ibid., 153.

28. "Operations Log," July 28, 1949.

29. Bergin, ed., *50 Years of Army Computing*, 54.

30. During the Cold War the National Center for Atmospheric Research never received funding on the scale of Los Alamos, but it was a lead customer for Cray supercomputers and the only site ever to receive a Cray-3 supercomputer (in 1993).

31. Aspray, *John von Neumann and the Origins of Modern Computing*, 137.

32. Ibid., 121.

33. Sayler to Richelderfer, September 29, 1949, JGC-MIT, box 9, folder 299.

34. Jule G. Charney, Ragnar Fjørtoft, and John von Neumann, "Numerical Integration of the Barotropic Vorticity Equation," *Tellus* 2, no. 4 (1950): 237–254, quotation from p. 254.

35. Harper, *Weather by the Numbers*, 141.

36. Clippinger to Charney, December 12, 1949, JGC-MIT, box 9, folder 299.

37. Holberton to Charney, February 7, 1950, JGC-MIT, box 9, folder 299.

38. Ibid.

39. Platzman, "The ENIAC Computations of 1950—Gateway to Numerical Weather Prediction," quotation from p. 307.

40. Charney to von Neumann, July 15, 1949, JvN-LOC, box 15, folder 2.

41. "Skeet" (Hauff) to Charney, April 26, 1950, JGC-MIT, box 9, folder 302. Charney wrote back with fond memories of their "shenanigans together" and inquiries as to Hauff's wife

and her baby, suggesting a fairly warm relationship between the visiting scientist and the computer operator.

42. Platzman, "The ENIAC Computations of 1950—Gateway to Numerical Weather Prediction."

43. Charney to von Neumann, July 15, 1949, JvN-LOC, box 15, folder 2.

44. Aspray, *John von Neumann and the Origins of Modern Computing*, 143. Platzman, "The ENIAC Computations of 1950—Gateway to Numerical Weather Prediction" mentions the difficulties caused by scaling on p. 311, and this is confirmed by the log-book entries.

45. Charney to Hauff, September 6, 1950, JGC-MIT, box 9, folder 302.

46. "Operations Log," March 9, JGC-MIT, box 9, folder 301.

47. Ibid., March 13.

48. "The time interval used was at first one hour but was increased to two and then three hours when it was found that the larger intervals gave practically identical forecasts and did not lead to computational instability." Charney, Fjørtoft, and von Neumann, "Numerical Integration of the Barotropic Vorticity Equation."

49. Platzman, "The ENIAC Computations of 1950—Gateway to Numerical Weather Prediction," quotation from p. 310.

50. Ibid. The log book records several instances of procedures being repeated because steps had been missed in preparing the input deck.

51. Charney, Fjørtoft, and von Neumann, "Numerical Integration of the Barotropic Vorticity Equation."

52. Platzman, "The ENIAC Computations of 1950—Gateway to Numerical Weather Prediction," 310.

53. Joseph Smagorinsky, quoted in Aspray, *John von Neumann and the Origins of Modern Computing*, 143.

54. Aspray, *John von Neumann and the Origins of Modern Computing*, 146–147.

55. Ibid., 146. According to Charney, Fjørtoft, and von Neumann ("Numerical Integration of the Barotropic Vorticity Equation"), an ENIAC forecast took a little over 24 hours, but it was estimated that "with a thorough routinization of operations" the time taken using ENIAC could be halved.

56. The Institute for Advanced Studies' computer had 1,024 words of delay-line storage and 2,048 words of drum storage, with 40 bits per word (ibid., 87). ENIAC took about 20 add times, or 4,000 microseconds, to multiply at the time that the forecasts were run. Fritz, *Description of the ENIAC Converter Code*, 24. The IAS computer is reported to have taken 713 microseconds.

57. Relative timings of ENIAC versus the IAS machine are from ibid., 145.

58. Brainerd to Goldstine, May 6, 1944, MSOD-UP, box 48 (PX-2 General Jan-Jun 1944).

59. Goldstine, *A Report on the ENIAC*, VII-13.

60. J. von Neumann to K. von Neumann, December 7, 1948, KvN-MvNW.

61. Fritz, *Description of the ENIAC Converter Code*, 7.

62. ENIAC followed something akin to the later technique of "prefetching" instructions from memory, in that execution of one instruction overlapped with fetching of the next. The durations quoted assume sequential execution. Thus, the times given for the simplest operations such as addition (six add times after the initial conversion) were fixed by the time taken to fetch the next instruction. For more complex operations such as multiplication (twenty add times after the initial conversion), ENIAC triggered its "basic sequence" (analogous to later fetch and decode cycles) part way through so that the next instruction would arrive just when it was needed. Executing a branch would mean that the next instruction to be executed had not already been fetched, causing it to take longer than usual. "Detailed Programming of Orders, ENIAC Converter Code," ENIAC-NARA (ENIAC Converter Code Book Used Before Installation of Shifter and Magnetic Core Memory).

63. "Aberdeen Proving Ground Computers: The ENIAC." An early design for the high-speed table is given in an untitled document in ENIAC-NARA, box 4, folder 14. This notes that it would take one add time to transmit the desired address to the high-speed function table and half an add time to receive its contents, though it also noted further modifications that could reduce the total to one add time. Instruction durations late in the machine's career are given in "Listing of Add Times of ENIAC Converter Code," June 1, 1954, ENIAC-NARA, box 4, folder 1.

64. J. Cherney, "Computer Research Branch Note No. 40: High Speed Shifter," ENIAC-NARA, box 4, folder 1.

65. "Changes to BRLM 582 'ENIAC CONVERTER CODE'," circa June 1954, ENIAC-NARA, box 4, folder 1.

66. Wrublewski, "ENIAC Operating Experience." We are not sure what might have been eliminated.

67. "Sidelights on the Financial and Business Developments of the Day: Military Memory," *New York Times,* December 20, 1952.

68. "Revised Specifications for Static Magnetic Memory System for ENIAC," October 9, 1951, ENIAC-NARA, box 4, folder 1.

69. The new instructions defined two versions of store and two of extract. One variant of each used indirect addressing and the other acted on a fixed address specified as an argument stored immediately after the instruction. These took between five and seven add times to execute, even though the memory itself could retrieve a number in only one add time. That made the core memory about twice as slow as accumulator memory. "Changes to BRLM 582 'ENIAC CONVERTER CODE'," circa June 1954, ENIAC-NARA, box 4, folder 1.

70. Wrublewski, "ENIAC Operating Experience." Specific reliability issues with the core memory were discussed further in Melvin Wrublewski, "An Engineering Report on the ENIAC Magnetic Memory," *Ordnance Computer Newsletter* 2, no. 2 (1955): 11–13 (in HHG-APS series 4, box 1).

71. Fritz, *Description of the ENIAC Converter Code*.

72. Michael R. Williams, "The Origins, Uses, and Fate of the EDVAC," *IEEE Annals of the History of Computing* 15, no. 1 (1993): 22–38.

73. Kempf, *Electronic Computers Within the Ordnance Corps*, 54.

74. Williams, "The Origins, Uses, and Fate of the EDVAC," quotation from p. 37.

75. Kempf, *Electronic Computers Within the Ordnance Corps*.

76. Williams, “The Origins, Uses, and Fate of the EDVAC.”

77. Spence (“Operating Time and Factors Affecting It … ”) gives a figure of 3,063 tubes in ORDVAC as of early 1953. The number would vary over time as new capabilities were added to the machines.

78. “Aberdeen Proving Ground Computers,” *Digital Computer Newsletter* 5, no. 2 (1953): 7–8.

79. Ibid.

80. When the BRL tallied the results for that year, ENIAC continued to spend less time on problem set-up and code checking than either of the new machines. In an average week it spent 79.4 hours running production jobs, versus 30.4 for EDVAC and 53.7 for ORDVAC. “Aberdeen Proving Ground Computers,” *Digital Computer Newsletter* 6, no. 1 (1951): 2.

81. Williams, “The Origins, Uses, and Fate of the EDVAC.”

82. Kempf, *Electronic Computers Within the Ordnance Corps*.

83. J. F. Cherney, “Branch Report No. 48: Modifications of the ENIAC’s IBM Input-Output Sign Sensing System,” November 9, 1953, NARA-ENIAC, box 2, folder 10.

84. “Aberdeen Proving Ground Computers,” *Digital Computer Newsletter* 6, no. 4 (1954): 2. EDVAC’s speed seems to have overwhelmed the supply of coded problems, as it spent 60 hours a week idle to ENIAC’s two

85. Wrublewski, “ENIAC Operating Experience.”

86. “Aberdeen Proving Ground Computers,” *Digital Computer Newsletter* 7, no. 3 (1954): 1.

87. Computer History Museum, “ENIAC (in online Revolution exhibit),” n.d., accessed January 23, 2015 (http://www.computerhistory.org/revolution/birth-of-the-computer/4/78). The same claim is made in Williams, “The Origins, Uses, and Fate of the EDVAC.”

Chapter 11

1. Doron Swade, “Inventing the User: EDSAC in Context,” *Computer Journal* 54, no. 1 (2011): 143–147, quotation from p. 145.

2. Eckert, “The ENIAC.” Eckert also noted that von Neumann was “particularly interested” in the “three-address instruction code” they had already formulated for EDVAC in which “we were going to tell the computer the location of two operands and the location for storing the result.” However, as Burks later noted, von Neumann is explicitly credited with the substitution order, the basis for address modification, in Eckert and Mauchly, Automatic High Speed Computing. That is a crucial feature, without which the radical simplicity of the modern code paradigm would not be possible.

3. Mauchly, “Amending the ENIAC Story.”

4. Notes of meeting with Dr. Von Neumann, March 14, 1945, AWB-IUPUI.

5. This is easiest to find as a reprint at the end of Eckert, “The ENIAC.” However, a draft copy, with certain corrections marked up, can be found as “Disclosure of Magnetic Calculating Machine”, January 29, 1944, UV-HML, box 7 (ENIAC Moore School of Electrical Engineering Disclosure of Magnetic Calculating Machine).

6. Stern, *From ENIAC to Univac*, 75.

7. McCartney, *ENIAC*, 124.

8. Burks and Burks, *The First Electronic Computer*, 150 shows Mauchly making this point during his testimony in the patent trial.

9. Burks and Burks, *The First Electronic Computer*, 265-267.

10. For example, "the instructions given to a single program control are referred to as a *program*," Goldstine, *A Report on the ENIAC*, I-21; "accumulator 3 is programmed to transmit," "ENIAC Progress Report 31 December 1944," IV-21.

11. "ENIAC Progress Report 31 December 1943," III-3. Note the distinction made here between the "programs" (individual operations) and "interconnections" (to make a set-up for a problem).

12. "ENIAC Progress Report 30 June 1944," IV-10.

13. Eckert, "Disclosure of Magnetic Calculating Machine."

14. "The Function Generator," PX Report, November 2, 1943, MSOD-UP, box 3 (Reports on Project PX). By the end of the year, this had been superseded by a more passive "function table" which did not provide built-in interpolation facilities. "ENIAC Progress Report 31 December 1943," chapter XI.

15. Staff of the Harvard Computation Laboratory, *A Manual of Operation for the Automatic Sequence Controlled Calculator* (Harvard University Press, 1946), 28, 50.

16. Quoted in Burks and Burks, *The First Electronic Computer*, 101.

17. In January of 1944 the ENIAC team was in close contact with the team at Bell Labs working on calculators controlled by paper tape (Herman H. Goldstine, "Report of a conference on computing devices at the Ballistic Research Laboratory on 26 January 1944," February 1, 1944, ETE-UP). Although the text provides no specific evidence it is certainly plausible to suppose that Eckert imagined that a calculator equipped with paper tapes might read instructions from them as well as numbers.

18. The text of the disclosure provides only one reason to believe that he imagined using its disks or drums to store what we would think of as programs. Although Eckert focused on permanently etched disks for "automatic programming" he mentioned as an aside that recordable magnetic disks could also be used. Erasable disks hold an obvious appeal for the storage of what we think of as programs, but it is also quite possible that he imagined updating the control codes to develop new mathematical functions for the calculator or to modifying existing ones. The benefits of this approach were well established in later generations of technology, for example the IBM 370 mainframes of the 1970s read their microcode from floppy disks and modern computers and smartphones can flash upgrades to firmware.

19. An initial list of patentable ideas from ENIAC and early work on what became EDVAC was prepared by Eckert and Mauchly as "Main Outline of Material for Patent Applications." This was presented "roughly in the order in which they should be considered" and bore a note that it was typed later from an original dated February 5, 1945. The ideas included delay-line registers, delay-line computing circuits, ideas on the use of tubes for computing, electronic ring counters, various features of the designs for ENIAC's accumulators, function tables, multiplier, cycling unit, "programming system, divider, and master programmer" (such as "digit control of steppers") and a long list of "input and output devices" such as "supersonic card readers." The final item was a list of "design considerations." In other words the list included a lot of speculative new ideas on components connected with EDVAC but the only control innovations mentioned were from ENIAC. A later and better-developed list was headed "Supplemental Outline—Devices for Computing" and included dozens of ideas over

eight pages such as schemes for detecting errors in pulse trains and devices for printing from magnetic tape at high speed. Again, no discussion of new control systems or architecture was included. We located copies of both documents in AWB-IUPUI with stamps showing that they had been reproduced from UV-HML but are unsure of the box number within the original collection.

20. Von Neumann, "First Draft of a Report on the EDVAC," section 1.2.

21. Campbell-Kelly and Williams, eds., *The Moore School Lectures*.

22. Michael R. Williams and Martin Campbell-Kelly, eds., *The Early British Computer Conferences* (MIT Press, 1985); Hartree, *Calculating Machine*; Hartree, *Calculating Instruments and Machines*; Engineering Research Associates, *High-Speed Computing Devices*.

23. Engineering Research Associates, *High-Speed Computing Devices*, chapter 10, pp. 182–222.

24. W. H. McWilliams, "Keynote Address," *Review of Electronic Digital Computers: Joint AIEE-IRE Computer Conference (Dec. 10–12, 1951)* (American Institute of Electrical Engineers, 1952): 5–6.

25. Nathaniel Rochester, "A Calculator Using Electrostatic Storage and a Stored Program," May 17, 1949, From the IBM Corporate Archives, Somers, New York. Its system of two-digit instruction codes and three-digit addresses for the stored program was very similar to the format adopted for the converted ENIAC.

26. This was in an end-of-year summary of developments in "Electronic Computers" for an engineering audience. "Radio Progress During 1950," *Proceedings of the IRE* 39, no. 4 (1951): 359–396, quotation from p. 375.

27. C. E. Frizzell, "Engineering Description of the IBM 701 Calculator," *Transactions of the IRE* 41, no. 10 (1953): 1275–1287, quotation from p. 1275.

28. J. W. Sheldon and Liston Tatum, "IBM Card-Programmed Calculator," in *Papers and Discussions Presented at the Dec. 10–12, 1951, Joint AIEE-IRE Computer Conference* (Association for Computing Machinery, 1951): 30–36, quotation from p. 35.

29. Walker H. Thomas, "Fundamentals of Digital Computer Programming," *Proceedings of the IRE* 41, no. 10 (1953), quotations from pp. 1245 and 1249.

30. Willis H. Ware, *The History and Development of the Electronic Computer Project at the Institute for Advanced Study* (RAND Corporation, 1953), p. 5.

31. International Business Machines Corporation, "Magnetic Drum Data Processing Machine Announcement," IBM Archives, 1953, accessed November 11, 2014 (https://www-03.ibm.com/ibm/history/exhibits/650/650_pr1.html). This is an interesting place in which to discover the term as the 650 combined computer and punched-card technologies, storing a program internally on a drum while relying on external plugboards to configure its input and output formats. This dual system echoed the two kinds of program control on the test assembly that had originally motivated the new coinage. The release observed that the 650 "combines one of the advanced memory devices and the stored program concept of IBM's big '701' … with new high speed reading capacity in the conventional punched card equipment."

32. Goldstine, *The Computer*.

33. Burks and Burks, "The ENIAC," p. 385.

34. Comment by B. Randell, *Annals of the History of Computing* 3, no. 4 (1981) 396–397.

35. Brainerd, “Project PX—The ENIAC.”

36. Campbell-Kelly, “Programming the EDSAC.”

37. Campbell-Kelly and Aspray, *Computer*, 104.

38. Allan G. Bromley, Stored Program Concept: The Origin of the Stored Program Concept, Technical Report 274, Brasser Department of Computer Science, University of Sydney, modified November 1985 (http://sydney.edu.au/engineering/it/research/tr/tr274.pdf).

39. B. Jack Copeland, *Turing: Pioneer of the Information Age* (Oxford University Press, 2013).

40. Campbell-Kelly and Aspray, *Computer*.

41. Mark Priestley argues in *A Science of Operations: Machines, Logic, and the Invention of Programming* (Springer, 2011) that the general connection between Turing’s computational model and actual stored-program computers was only widely recognized after 1950.

42. For example, in Raúl Rojas, “How to Make Zuse’s Z3 a Universal Computer,” *IEEE Annals of the History of Computing* 20, no. 3 (1998): 51–54.

43. Wikipedia, “Stored-Program Computer,” accessed October 17, 2012.

44. Paul Ceruzzi, *Computing: A Concise History* (MIT Press, 2012), 29.

45. Swade, “Inventing the User,” quotation from p. 146.

46. That claim is discussed further in Thomas Haigh, “Actually, Turing Did Not Invent the Computer,” *Communications of the ACM* 57, no. 1 (2014): 36–41.

47. Bartik, *Pioneer Programmer*, xx.

48. Clippinger, Oral History Interview with Richard R. Mertz, 11–12.

49. Goldstine, *The Computer*, p. 233. Goldstine’s personal papers, HHG-APS and HHG-HC, include several documents that confirm the earlier operation of ENIAC with the new control method. The date he gave in the book appears to be based on the title of a BRL document in HHG-APS titled “ENIAC: Details of CODE In effect on 16 September, 1948.” That, of course, provides no more than a later bound for its first operation after conversion to the modern code paradigm.

50. Neukom, “The Second Life of ENIAC.”

51. Metropolis and Worlton, “A Trilogy on Errors in the History of Computing,” quotations from pp. 53–54. This was originally presented at a conference in 1972. At that point Metropolis may not have been aware of the Manchester Baby.

52. Goldstine, *The Computer*, 233.

53. Aspray, *John von Neumann and the Origins of Modern Computing*, 238–239.

54. Burks, unfinished book manuscript, appendix B.

55. Burks, “Review of William Aspray Ms. ‘The Stored Program Concept,’ for Spectrum,” July 11, 1990, AWB-IUPUI.

56. The influence of the Williams Tube on the work of von Neumann’s group at the Institute for Advanced Studies is related in Dyson, *Turing’s Cathedral*, 142–148.

57. The Baby’s parts were soon used to build a complete and useful computer, now known as the Manchester Mark I, which was fully operational by late 1949. However, we focus here on the Baby, as it is generally accepted as the first “stored program” computer to operate, or

in some formulations the first machine to run a stored program, and hence it provides a natural comparison point.

58. Allan Olley, "Existence Precedes Essence—Meaning of the Stored-Program Concept," in *History of Computing: Learning from the Past*, ed. A. Tatnall (Springer, 2010).

59. For a nuanced account of the SSEC's use of relay memory for instructions, see Charles J. Bashe, Lyle R. Johnson, John H. Palmer, and Emerson W. Pugh, *IBM's Early Computers* (MIT Press, 1986), 586–587. This account describes a procedure by which a five-instruction subroutine could be executed from relay memory, but admits that "it is more likely, in fact, that all but the final line [an instruction in which the source of the next instruction was modified to terminate the loop] would be stored in a pair of subsequence tapes."

60. Comprehensive technical details on the SSEC, even on basic elements such as its instruction set, have not been published. The most detailed surviving descriptions we were able to locate are in an incomplete, unpublished, undated manuscript by A. Wayne Brooke, "SSEC. The First Selectronic Computer (with markup from C. J. Bashe)," in AWB-NCSU, box 1, folder 14.

61. Descriptions respectively from Paul E. Ceruzzi, *Computing: A Concise History* (MIT Press, 2012), 50, Campbell-Kelly and Aspray, *Computer*, 104, and Campbell-Kelly and Aspray, *Computer*, photo inset.

62. David Hartley, "EDVAC 1 and After—A Compilation of Personal Reminiscences," University of Cambridge Computer Laboratory, last modified July 21, 1999, accessed January 23, 2015 (http://www.cl.cam.ac.uk/events/EDSAC99/reminiscences/).

63. Campbell-Kelly, "Programming the EDSAC."

64. For example, once a virtual computer built within Conway's Game of Life was shown to be computationally equivalent to a Universal Turing Machine, that single fact told us that with sufficient time and a large enough cellular matrix that computer could execute the same algorithms as any machine built from conventional components.

65. Michael S. Mahoney with Thomas Haigh, ed., *Histories of Computing* (Harvard University Press, 2011).

66. Ibid., 91.

67. Rojas, "How to Make Zuse's Z3 a Universal Computer."

68. Zuse claimed to have devised the "stored program concept" in 1937 but decided that "in 1938, given the state of the technology, it would not have been wise to use the von Neumann architecture." Konrad Zuse, *The Computer—My Life* (Springer, 1993), 44 and 50.

69. For example, the entry on ENIAC in Wikipedia (accessed January 23, 2015) asserts that "it was Turing-complete, digital, and capable of being reprogrammed." A Web search locates hundreds of instances of the same claim.

70. Calvin C. Elgot and Abraham Robinson, "Random-Access Stored-Program Machines, an Approach to Programming Languages," *Journal of the ACM* 11, no. 4 (1964): 365–399.

71. Raúl Rojas, "Who Invented the Computer? The Debate from the Viewpoint of Computer Architecture," *Proceedings of Symposia in Applied Mathematics* 48 (1994): 361–365.

72. By contrast, the read-only memory in the function tables was fully addressable, and "modern" search algorithms, for example, could be (and in the Monte Carlo programs, were) written in the converter code.

73. “Changes to BRLM 582 ‘ENIAC Converter Code’,” circa June 1954, ENIAC-NARA, box 4, folder 1.

74. What if one plays the theorists’ traditional game of exploring what a machine could do if granted vast amounts of time and storage but left otherwise unchanged? To make the accumulators addressable, one could simply write a pair of subroutines: one to store and one to load. Each would take as a parameter an accumulator number, which would be used to calculate a jump to the function-table address at which the appropriate “listen” or “talk” instruction has been placed. That would tie up two rows of a function table for each accumulator rendered addressable, but unlimited storage would already have been assumed. See our online appendix “How to Make ENIAC’s Accumulators Addressable Using a Subroutine,” available at www.EniacInAction.com.

75. For a rather aggressive critique of the impressionistic use made of the ideas of the universal computer and Turing machine by some prominent historians, see Edgar G. Daylight, “Difficulties of Writing About Turing’s Legacy,” Dijkstra’s Rallying Cry for Generalization, last modified September 3, 2013 (http://www.compscihistory.com/DifficultTuringLegacy).

Chapter 12

1. D. R. Hartree, “The ENIAC: An Electronic Calculating Machine,” *Nature*, 157 no. 3990 (1946): 527; “The ENIAC: An Electronic Calculating Machine,” *Nature*, 158 no. 4015 (1946): 500–506; *Calculating Machines; Calculating Instruments and Machines*.

2. Berkeley, *Giant Brains or Machines That Think,* p. 113.

3. David H. Ahl, ed., *The Colossal Computer Cartoon Book* (Creative Computing Press, 1977).

4. Internet users have formalized this joke as an apocryphal war of press releases between Microsoft and General Motors. See, e.g., http://www.snopes.com/humor/jokes/autos.asp.

5. Lynn Grant, “Conserving ENIAC (aka Project CLEANIAC),” http://www.penn.museum/blog/museum/conserving-eniac-aka-project-cleaniac/, accessed June 30, 2014.

6. Geise to Burks, April 8, 1960, AWB-IUPUI.

7. Burks to Giese, February 18, 1985, AWB-IUPUI.

8. An online version of the museum’s display can be found at http://www.nwmissouri.edu/archives/computing/index.htm.

9. Brendan I. Koerner, “How the World’s First Computer Was Rescued from the Scrap Heap,” *Wired*, November 25, 2014 (http://www.wired.com/2014/11/eniac-unearthed/).

10. Mitch Meador, “ENIAC: First Generation of Computation Should Be a Big Attraction at Sill,” *Lawton Constitution* (swoknews.com)*,* October 29, 2014.

11. Burks, *Who Invented the Computer?*

12. Larson, *Findings of Fact*, section 11.13.

13. Most recently, though without apparent conviction, in Smiley, *The Man Who Invented the Computer*.

14. McCartney, *ENIAC*.

15. Burks, *Who Invented the Computer?*

16. “Preliminary Announcement: International Research Conference on the History of Computing,” in AWB-IUPUI.

17. The three credentialed historians were I. Bernard Cohen, Henry S. Tropp, and Kenneth O. May.

18. In collection of material from the Los Alamos conference in AWB-IUPUI.

19. Goldstine to Smith, May 14, 1959, HHG-APS, series 6, box 1.

20. Randell, “The Colossus.”

21. Burks and Burks, “The ENIAC,” 311. “General purpose” is defined on page 385.

22. Paul E. Ceruzzi, *Reckoners: The Prehistory of the Digital Computer, from Relays to the Stored Program Concept, 1935–1945* (Greenwood, 1983).

23. Paul Ceruzzi, then entering the field as a doctoral student, recalls a direct influence from the 1970s discussion of whether programmable calculators were computers (private discussion with authors, November 4, 2011). This is reflected in a contemporary discussion by the computer pioneer Fred Gruenberger, who argued that stored-program capability was the true dividing line between computers and calculators. See Gruenberger, “What’s in a Name?” *Datamation* 25, no. 5 (1979): 230.

24. The influence of electronic calculators on the historical debate was mentioned to us by Paul Ceruzzi. Misguided pedants continue to try to impose it—for example, the Wikipedia page for ENIAC has repeatedly been changed to suggest that the C in ENIAC stood for “calculator.” The incorrect version is found in many online sources, and even some books present the question as unsettled. “There is some confusion regarding precisely what ‘ENIAC’ stood for,” according to Mike Hally, *Electronic Brains: Stories from the Dawn of the Computer Age* (Granta Books, 2006), 12.

25. Al Gore, “The Technology Challenge How Can America Spark Private Innovation?,” *University of Pennsylvania Almanac,* February 20, 1995.

26. Bergin, ed., *50 Years of Army Computing*, vi.

27. The quotations are from Jan Van Der Spiegel, “ENIAC-on-a-Chip,” *PennPrintout* 12, no. 4 (1996). The project is described in more detail in Jan Van der Spiegel et al., “The ENIAC—History, Operation and Reconstruction in VLSI,” in *The First Computers: History and Architectures*, ed. Raúl Rojas and Ulf Hashagen (MIT Press, 2000).

28. Til Zoppke and Raúl Rojas, “The Virtual Life of the ENIAC: Simulating the Operation of the First Electronic Computer,” *IEEE Annals of the History of Computing* 28, no. 2 (2006): 18–25.

29. Jon Agar, Sarah Green, and Penny Harvey, “Cotton to Computers: From Industrial to Information Revolutions,” in *Virtual Society? Technology, Cyberbole, Reality*, ed. Steve Woolgar (Oxford University Press, 2004).

30. Huskey is, as of this writing, 98 years old. His name doesn’t appear in the Moore School lectures volume either as an instructor or as a student, but he did lead a computer project that began in the 1940s: the Standards West Electronic Computer (SWAC). He may be the last survivor of any computer project of that decade.

31. Burks, *Who Invented the Computer?*, 17.

32. Smiley, *The Man Who Invented the Computer*.

33. A number of Amazon.com reviews by experts on digital computing identify specific errors; see http://www.amazon.com/The-Man-Who-Invented-Computer/product-reviews/0385527136. Some non-specialists were also unimpressed. Example: "The narrative shuffles painstakingly along; reading it is like watching a very old man pack for vacation. The characters feel morally and intellectually uninhabited, lighted from without rather than within. The scientific developments at the heart of modern life are never satisfactorily explained (except in the wonderfully lucid appendices)." Kathryn Schulz, "Binary Breakthrough," *New York Times,* November 26, 2010.

34. Fritz, "ENIAC—A Problem Solver" and "The Women of ENIAC."

35. Thomas Petzinger, "The Front Lines: History of Software Begins with the Work of Some Brainy Women," *Wall Street Journal,* November 15, 1996.

36. Light, "When Computers Were Women," 469.

37. *Technology and Culture* is the most respected journal for history of technology. At the time of writing, Web of Knowledge lists Light's as the second most widely cited paper published in that journal and records more citations for it than for any paper ever published in *IEEE Annals of the History of Computing*.

38. Ada Lovelace is described as "computer pioneer" on an English Heritage "blue plaque" attached to her former home in London's St. James' Square.

39. Bartik, "Hendrie Oral History, 2008," 30 and 34.

40. Ibid., 58.

41. Ibid.

42. For a salient discussion, see Judith A. McGaw, "No Passive Victims, No Separate Spheres: A Feminist Perspective on Technology's History," in *In Context: History and the History of Technology*, ed. Stephen Cutcliffe and Robert Post (Lehigh University Press, 1989).

43. Walter Isaacson, *The Innovators: How a Group of Hackers, Geniuses, and Geeks Created the Digital Revolution* (Simon and Schuster, 2014), 107.

Conclusion

1. For example, Abbate (*Recoding Gender: Women's Changing Participation in Computing*, 26) uses a quotation from Mauchly to support the judgment that "programming was an afterthought." According to Nathan Ensmenger (*The Computer Boys Take Over: Computers, Programmers, and the Politics of Technical Expertise*, MIT Press, 2010, 15), the discovery that setting up ENIAC to execute a computing plan would "turn out to be difficult and require radically innovative thinking" was "completely unanticipated."

2. Michael S. Mahoney, "The Histories of Computing(s)," *Interdisciplinary Science Review* 30, no. 2 (2005): 119–135, quotation from p. 121.

3. I. Bernard Cohen, *Howard Aiken: Portrait of a Computer Pioneer* (MIT Press, 1999).

4. Ensmenger, *The Computer Boys Take Over*, 32.

5. "ENIAC Progress Report 31 December 1943," chapter XIV.

6. Stephen R. Barley, "Technicians in the Workplace: Ethnographic Evidence for Bringing Work into Organizational Studies," *Administrative Science Quarterly* 41, no. 3 (1996): 404–441.

7. The incident was described in several oral-history interviews and most recently in Bartik, *Pioneer Programmer*. On page 80, Bartik states that "Kay's exclamation was a breakthrough!"

8. Goldstine, *A Report on the ENIAC*, quotations from pp. I-10, I-20, II-15, and IV-9.

9. Ensmenger, *The Computer Boys Take Over*, 14–15, 36–39. Goldstine and von Neumann ("Planning and Coding Problems for an Electronic Computing Instrument. Part II, Volume 1," 99–104) outline a methodology for planning and coding problems, but do not to appear to propose a firm division of labor or to define coding as a clerical task. They suggest that "every mathematician, or every moderately mathematically trained person, should be able to do [the coding] in a routine manner."

10. See, for example, Abbate, *Recoding Gender* and Beyer, *Grace Hopper*.

11. Light, "When Computers Were Women," 470.

12. Ensmenger, *The Computer Boys Take Over*, 32.

13. Ensmenger, *The Computer Boys Take Over*, 35–39. Ensmenger writes on page 37 that the ability of the operators to recognize a failed vacuum tube suggests that they "were able to interact much more with the computer engineers and technicians than was probably originally intended."

14. Abbate, *Recoding Gender: Women's Changing Participation in Computing*, p. 26 and note 43 on p. 185. In fact the idea of "coding" does not appear to have been applied to the work of producing ENIAC set-ups in project progress reports or in Goldstine's *Report on the ENIAC*. It may have gained currency after the propagation of the modern code paradigm in the First Draft. This makes sense in view of the familiarity of things like Morse Code. EDVAC programs were to be represented as a series of numerical codes, like those of the Harvard Mark I (where the term found an early foothold), whereas ENIAC set-ups were recorded graphically.

15. Beyer, *Grace Hopper*, 52–58. Of course, the task of the Mark I's operators was simpler than that of ENIAC's operators.

16. The argument is made at greater length in Thomas Haigh, "Masculinity and the Machine Man," in *Gender Codes: Why Women are Leaving Computing*, ed. Thomas J. Misa (IEEE Computer Society Press, 2010.

17. Galison and Hevly, *Big Science: The Growth of Large-Scale Research*.

18. Latour, *Science in Action: How to Follow Scientists and Engineers through Society*.

19. Akera, *Calculating a Natural World*; Akera, "Constructing a Representation for an Ecology of Knowledge: Methodological Advances in the Integration of Knowledge and its Various Contexts," *Social Studies of Science* 37, no. 3 (2007): 413–441.

20. Andrew Pickering, "The Mangle of Practice: Agency and Emergence in the Sociology of Science," *American Journal of Sociology* 99, no. 3 (1993): 559–589.

21. Michael S. Mahoney, "The Beginnings of Algebraic Thought in the Seventeenth Century," in *Descartes: Philosophy, Mathematics and Physics*, ed. S. Gaukroger (Harvester, 1980).

22. Michael S. Mahoney, "Calculation—Thinking—Computational Thinking: Seventeenth-Century Perspectives on Computational Science," in *Form, Zahl, Ordnung. Studien zur Wissenschafts- und Technikgeschichte. Ivo Schneider zum 65. Geburtstag*, ed. Menso Folkerts and Rudolf Seising (Frank Steiner Verlag, 2004).