Naval War College Review

Volume 52
Number 3 *Summer*

Article 5

1999

Scientist in Uniform: The Harvard Computation Laboratory in World War II

Kathleen Broome Williams

Scientists in Uniform
The Harvard Computation Laboratory in World War II

Kathleen Broome Williams

IN SPRING 1998, CONSTRUCTION of the new Maxwell Dworkin computer sciences building began at the northeast corner of Harvard University's Holmes Field. The site had once housed the Aiken Computation Laboratory, scathingly described in the previous fall's *Harvard Magazine* as a "cobbled together structure unloved by those who toiled there."[1]

Two years before, Harvard dropout Bill Gates and his Microsoft associate and Harvard classmate Steven Ballmer together had given twenty-five million dollars to Harvard to endow a faculty chair and to build a new computer science facility. But instead of continuing to honor the name of Howard Hathaway Aiken—founder of Harvard's trailblazing computing program and a naval reserve officer who directed the Navy's original research and applications of computers—the new center is to be named for the mothers of the two recent benefactors.[2]

Today's Navy might learn much from the latitude Aiken was given during World War II to fuse academic and scientific activities with operational naval needs in a pragmatic arrangement benefiting all. In the process, Howard Aiken launched the Navy on its first stumbling steps towards today's vastly different conceptions of naval operations and modern warfare. Aiken and his coworkers, such as Lieutenant Grace Hopper, began what was arguably the most important development in naval technology in the twentieth century, affecting the nature and use of virtually all other technologies. Their accomplishments deserve greater recognition.

Dr. Williams teaches history at Bronx Community College of the City University of New York. She is the author of *Secret Weapon: U.S. High-Frequency Direction Finding in the Battle of the Atlantic* (Annapolis, Md.: Naval Institute Press, 1996), a cocompiler of *The Commissioned Sea Officers of the Royal Navy, 1660–1815* (Brookfield, Vt: Ashgate, 1994), and a contributor to the *Civil War Book of Lists*. She holds a bachelor's degree from Wellesley, a master's from Columbia University, and a doctorate in history from the City University of New York. Her current research specialization is the role of women in the development of naval technology.

This work was supported by a grant from the City University of New York PSC-CUNY Research Award Program.

Naval War College Review, Summer 1999, Vol. LII, No. 3

Although the rapidly expanding data management needs of World War II accelerated the development of modern digital computers, especially in Britain and the United States, few were operational until after the conflict ended. A notable exception in America was the brainchild of Howard Aiken, the culmination of a project he began in 1937 as a graduate student at Harvard.

Frustrated by the tedious and time-consuming mathematical calculations required for his doctoral dissertation on the theory of space charge conduction, Aiken designed a mechanism to perform such calculations automatically. Engineers at Thomas Watson's International Business Machines—IBM—built Aiken's machine under his guidance but using many of their own patented parts. What emerged from this collaboration, the Automatic Sequence Controlled Calculator (ASCC) or Harvard Mark I, was the first functional, large-scale, automatically sequenced, general-purpose digital computer to be produced in America.[3] The press called it a "Robot Brain," but Aiken, by then a professor of physics and applied mathematics, called it "just a lazy man's dream," intended for use in scientific numerical computation.[4]

When the Mark I was finally completed at the IBM facilities in Endicott, New York, in 1944, Watson of IBM gave it to Harvard as a gift. That spring it was installed at the university but was immediately leased for the duration of the war by the U.S. Navy, desperate for gunnery and ballistics calculations.[5] Aiken, a naval reserve officer, was put in charge of the Mark I for the Bureau of Ships (BuShips) Computation Project at the Harvard Computation Laboratory.[6]

The Navy's role in running the Computation Laboratory has received scant attention, even in books on World War II naval technology, nor is Harvard's role as reluctant host of the lab widely known.[7] This neglect suggests how difficult was the alliance of academic, business, and military interests that Howard Aiken pulled together in the development and early use of the Mark I. For a time, Aiken and patriotism were able to hold together competing professional agendas. The Mark I successfully carried out a strenuous schedule of important calculations for the Navy and for other military projects. After the war, however, the centrifugal interests of each group reasserted themselves, obscuring Aiken's wartime achievements.

In two articles in November 1996, the *Wall Street Journal*—reflecting a widespread view—asserted that the U.S. Army–sponsored University of Pennsylvania Electronic Numerical Integrator And Computer (ENIAC) was the first "computer," even though it did not come into operation until 1946. This was almost two years after the Mark I and well after the end of the war.[8] Moreover, while it is true that the ENIAC was electronic (using vacuum tubes) and was therefore much faster than the electromechanical decimal counter system of the Mark I, it is not clear that speed is the defining requirement for a computer. The ENIAC, for example, was designed primarily for solving trajectory problems; unlike the Mark I, it could not be readily used as a general-purpose computer. Experts still disagree, on these and a number of other technical grounds, about which was the first "true" computer, so the issue for them—if not for the *Wall*

Street Journal—remains unresolved.[9] Yet the assertion of the ENIAC's primacy was not challenged by Harvard or by the Navy. Nor was any objection raised more recently when *Newsweek* overlooked the Mark I in an article on the history of computing in its Winter 1997–1998 special edition.[10]

What Watson may not have understood when he gave the Mark I to Harvard was that the university with which he wished to become associated had a tradition of indifference toward what it viewed as the "applied" sciences. As the *Encyclopedia of Computer Science and Engineering* diplomatically explains with regard to Howard Aiken's interest in computer technologies, "Harvard was not the most likely environment to get support for this type of research."[11] At Harvard, where pure theory was emphasized, Aiken found himself on the academic fringe—"a real outsider and upstart," according to Professor I. Bernard Cohen of Harvard's history of science faculty.[12] Indeed, there was so much institutional resistance at Harvard to the application-oriented science of computers that Aiken always had to struggle for funding.[13]

Harvard also aggravated Aiken's situation by seeming to snub Thomas Watson—at least in Watson's eyes—during the opening ceremony for the Mark I computer. Watson struck back by severely curtailing IBM's contributions to Aiken's project. With only halfhearted support from either Harvard or IBM, it was Aiken's relationship with the Navy that assured the survival of the lab in its early days.

The importance of the Mark I's numerical computing ability to the Navy was indicated by the presence of senior naval officers at its inauguration at Harvard on 7 August 1944. These included Rear Admiral Edward L. Cochrane, chief of the Bureau of Ships; Rear Admiral A. H. Van Keuren, director of the Naval Research Laboratory (NRL); and Rear Admiral Julius A. Furer, coordinator of research and development.[14] Admiral Furer, in particular, was a strong advocate of scientific development. Holding his position as coordinator from 13 December 1941 until his retirement after VE Day, he worked closely and well with the civilian scientific authorities, maintaining a smooth mechanism for liaison.[15]

At the inauguration the *Boston Daily Globe* ran a photograph of the "World's Greatest Calculator," noting that it had been invented by Commander Howard H. Aiken, U.S. Naval Reserve.[16] The "Algebra Machine," as the *New York Times* called the Mark I, was a trailblazer in a new and rapidly developing discipline.[17]

The computing machine taken over by BuShips in 1944 was in many ways unique. It was enormous, some fifty feet long and eight feet tall, filling an entire room. It had more than 750,000 parts, used 530 miles of wire, and weighed about five tons. A four-horsepower electric motor drove all the mechanical parts by a system of gears and chains, and over a thousand ball bearings kept its components moving.[18] Many sorts of electromechanical desk calculators were then in common use, and IBM punched-card machines were numerous, but the Mark I was "clearly not of the same species," according to Richard M. Bloch, a

Harvard mathematics graduate who wrote many of the machine's early programs.[19] Indeed the Mark I, built to exploit the ideas of the nineteenth-century British inventor Charles Babbage, was a rare creature, an electromechanical digital computer—destined to dominate the field for only a few years, briefly bridging the gap between calculators and electronic computers.[20]

Howard Aiken described the Mark I as a "general arithmetic machine capable of addition, subtraction, multiplication, division, and the transfer of numbers."[21] Most impressive were its speed of computation and its automatic functioning, enabling it to proceed through a series of arithmetic operations without human intervention. Automatic sequence control was accomplished according to instructions programmed on punched paper tape, while the output was handled either by punched cards or by two electric typewriters.

The multiple-purpose capabilities of the Mark I—the fact that it could be set to accomplish a wide range of different types of numerical calculations—constituted one of its great strengths and set it apart from other contemporary computing devices. For Aiken—who always wanted practical results—flexibility, accuracy, and reliability were even more important than speed, although he estimated that the Mark I was nearly a hundred times more productive than a manually operated calculator. The Mark I attained its accuracy by representing numbers to twenty-three significant digits. It ran twenty-four hours a day, functioning 90 to 95 percent of the time, with few interruptions, for fifteen years.[22]

Aiken was well aware of ongoing experimental work using vacuum tubes to replace relatively slow mechanical relays, but he believed it was worth sacrificing some speed to be able to put a device to use immediately. A postwar history of wartime computing developments bears out this judgment: "Electronic equipment held great promise in the high speed computing field but it appeared that the established techniques . . . [of] relays would permit earlier completion of large scale computing equipment."[23]

The BuShips contract for the Computation Project, which was to last until "six months after the cessation of present hostilities," was part of a pattern of increased military and government involvement in industry and academe.[24] As war threatened, intellectual resources all over the country—especially scientific and mathematical—had been enlisted to tackle the challenge of a vast technological expansion. Various agencies appeared under the Office of Emergency Management to mobilize and direct engineering and scientific talent. In June 1940, the National Defense Research Committee (NDRC) was established for this purpose, subordinated a year later to the more powerful Office of Scientific Research and Development (OSRD). As head first of NDRC and then of OSRD, Dr. Vannevar Bush, formerly of Massachusetts Institute of Technology, directed more than thirty thousand people working on such projects as radar, fire control, proximity fuses, and the atomic bomb.[25] At first, both the Navy and Army opposed the control of wartime scientific research by a civilian organization, even though they each had representation on the NDRC.[26] It was clear to one British scientific observer that in the beginning, "the Navy Dept. and Research Laboratory [NRL] were jealous, or in danger of feeling jealous, of Dr. Bush and his committee."[27]

Navy resistance to civilian influence continued to surface from time to time. In late 1943, Warren Weaver, of the Rockefeller Foundation, who headed the Applied Mathematics Panel (AMP) of NDRC (which supervised many war research contracts, including several with Aiken's lab), noted on one occasion that Commander Francis Bitter, head of the Air Technical Analysis Division, "has circulated a letter within the Navy in which he states that the AMP would be more effective if it were brought more directly under Navy supervision, the inference being that he do the supervising." Weaver had a different view: "We do not exactly propose to be swallowed."[28] Nor was he. By the time the Mark I was operational, NDRC's influence on Navy science was well established, made more palatable by generous research and development grants.

Importantly, traditional Navy suspicion of academic labs receded once it became clear to many that this war, unlike previous ones, might be won by technical and scientific advances made during the course of the war itself.[29] As a result, most Navy bureaus worked rather smoothly with the civilian scientific structure. This cooperation was facilitated by the very large proportion of scientists—civilians and former civilians temporarily in uniform—who were involved in war-related research in academic and corporate as well as in military laboratories.

Many academic applied research facilities were under some form of supervision by both NDRC and the Navy (or the Army); often "the actual allocation of responsibilities was complex."[30] This was certainly true in the case of the Harvard Computation Lab. While Howard Aiken technically reported to Commander David Ferrier, of the nearby Harvard Radio Research Laboratory, and to Commander Eugene Smith at BuShips, he also received instructions directly from the NDRC's Applied Mathematics Panel on projects to be assigned to his lab.[31] This situation was at times confusing, but hardly unique during the war. Such mixtures of civilian and military authority occurred in research facilities all over the country, including at other Harvard laboratories and schools. Nor was the Computation Lab the only case in which the Navy took over a whole structure. In 1942, the Naval Computing Machinery Laboratory was formed at National Cash Register's (NCR) plant in Dayton, Ohio. Eventually, the Navy took over all of NCR's cryptanalytic work.[32] But at the Computation Lab—an entirely naval reserve outfit—civilian and military leadership were fused in the person of Howard Aiken; the Navy put him in command of his own laboratory. Also, perhaps because of the small number of people involved and the innovative nature of the work, which few outsiders understood, Aiken was essentially autonomous, running his nominally Navy facility in his own idiosyncratic way.

It was undoubtedly the pressures of war that forced an initially reluctant Navy into some unprecedented arrangements—for example, accepting the technical assistance of scientifically educated women.[33] The Navy had little choice but to accommodate such oddball arrangements if it wished to get the scientific help it needed. The complex, interlocking structure of the American scientific war effort helps explain the significance of the work of the Mark I. By contrast with Germany, Britain, and Japan, American science benefited from a late entry into the war. Vannevar Bush had time to create an organization capable of connecting a wide variety of military and civilian resources in the solution of problems whose component parts were farmed out to many otherwise unconnected entities.[34] The Navy's Computation Lab became one of those entities, running calculations whose results formed part of the answers to many different kinds of technical military questions.

Of course, Aiken's lab was not the only one addressing the country's computing needs. During World War II, the United States manufactured approximately 45 percent of all armaments produced by all parties engaged in the conflict. Scientists and technicians worked at a feverish rate on the design, testing, modification, and analysis of these weapons, and their efforts required extensive numerical calculations. Trained specialists—usually women called "computers"—produced many of the numbers, using desk calculators. Wartime pressure, however, generated government contracts to create better and faster methods of computation.[35] The rapid progress made in the field was due in part to the solid groundwork laid earlier.

Between the two world wars, the growth of large-scale businesses had already sparked efforts to come to grips with modern calculation and record-keeping needs. Work progressed in several industrial as well as academic laboratories on improved calculators, and one or two early computer designs were produced. By 1930, Dr. Bush and his colleagues at MIT had developed a "differential analyzer"—a general-purpose, automatic analog computer, driven by electric motors, which could be set to work on most problems involving differential equations. Copies of the analyzer were eventually widely used in the war effort, especially to create firing and bombing tables. Similar, but simpler, analog machines were also used during the war for radar and gunnery.[36]

While Aiken was working on the ASCC/Mark I at IBM, Dr. George R. Stibitz was engaged in a similar effort at Bell Telephone Laboratories (BTL). On 8 January 1940, Stibitz put into operation a digital device called a "partially automatic computer," capable of performing addition, subtraction, multiplication, and division of complex numbers. By the mid-1940s, BTL had also completed machines roughly comparable to the Mark I in overall performance.[37] At the same time, at Iowa State College, mathematician John V. Atanasoff was working on a device that some consider the first electronic digital computer but that never became operational.[38]

Overseas, advanced computer developments were also in progress, accelerated by the war. In Germany in 1938, six years before the Mark I, engineer Dr. Konrad Zuse completed his Zuse 1, an electromechanical relay computer.

By 1943 he had completed the Zuse Z3, which was probably the first fully functional general-purpose digital computer, and which was used—though too late to affect the outcome of the war—in the German aircraft industry and in the engineering of V2 rockets.[39] In Britain, impending war brought a rush of computer developments focused on codebreaking applications. The "Colossus" series of machines, produced by mathematician Alan M. Turing and others for cryptanalysis, was one of the most important computer developments of the war. The first Colossus, an electronic proto-computer, became operational in January 1944, just at the time the Mark I was being installed at Harvard.[40]

While the true record of the Computation Lab's contribution to the war was obscured at the time by the secrecy of the work itself, the glamorous combination of Harvard cachet and Navy war service was apparently too appealing to succumb to censorship. The lab was so widely publicized during the war, through print and pictures in newspapers and magazines, that Aiken received requests for computing help from private individuals all over the country, even requests from schoolchildren for information for class projects.[41] Indeed, the Mark I—"Bessie" to those who worked with the machine later—became something of a poster girl, and her creator, Commander Aiken, a symbol of Navy scientific accomplishment.[42]

Aiken and his mathematicians were anomalies among academic and even service laboratories, in that they were almost all in uniform; this suited them well in their Navy propaganda role. In 1945, all eight scientists on Aiken's staff, including two women, were temporary naval reserve officers; in other laboratories engaged in war work, many academics shunned the very idea of military discipline. All eight technicians were Navy enlisted men too, and there were only six civilian support staff.[43] OSRD maintained a "Reserved List of Scientific and Technical Research Workers" to eliminate conflicts with the Selective Service. The minimum basis for inclusion on the list was "that the man is using his training and experience at a job for which he is specifically trained and on which he must use his analytical brain power."[44] Interestingly, all the male scientists at the wartime Computation Lab clearly qualified for exemption from the draft on occupational grounds; the women were exempt by gender; and Howard Aiken, who was forty-one when the United States entered the war, would also have been exempt from military service because of his age. Yet they were all in the Navy by choice, not only surrendering personal freedom but suffering considerable loss of pay.[45]

The unusual voluntary military status of the Harvard staff is even more surprising considering the intense competition for scientists among the services and with OSRD/NDRC. The resulting "pirating" from one agency to another increased the scientists' chances of avoiding the draft and maintaining civilian status.[46] Once the war began, the Navy moved to secure the services of eminent scientists, for in some quarters at least there was already an understanding of the importance of maintaining a technological edge. Columbia University astronomer Dr. Wallace Eckert, with his IBM machines, were recruited for secret work at the Naval Observatory in Washington, working directly for the Navy but as a civilian. In 1942, Dr. John Atanasoff left Iowa State College to join the staff of the Naval Ordnance Laboratory (NOL), and he too remained a civilian, though he was three years younger than Aiken.[47] In June 1944, the Navy tried, unsuccessfully, to lure physicist Dr. John W. Mauchly away from the University of Pennsylvania's Moore School of Electrical Engineering to work at NOL. He was told that "the Laboratory's need for men with the proper qualifications is urgent," but he declined the offer, even though he was only thirty-six (a year younger than Aiken's assistant, Lieutenant [junior grade] Grace Hopper) and would have remained a civilian.[48]

The U.S. Army also recognized the importance of civilians and civilian facilities to its scientific war needs. It too funded work at many academic and industrial laboratories, recruiting a formidable group of scientists. One of the most productive of these collaborations was between the University of Pennsylvania's Moore School and the Army Ordnance Department's Ballistic Research Laboratory at Aberdeen Proving Ground, Maryland; that work resulted in the ENIAC computer, designed for ballistics analysis.[49] The Moore School also carried out war research for the Army Signal Corps, the Navy Bureau of Ordnance (BuOrd), and OSRD. In 1944–45 it spent $350,000 on such projects as rockets, radar, the aerodynamics of projectiles, and antiaircraft fire control. More than a hundred employees of the Moore School were working on war projects by April 1945.[50]

By comparison, Harvard University took on over a hundred research contracts during the war, totaling $33,500,000. OSRD contracts employed 1,759 people, mostly civilian, while sixty-nine additional personnel were engaged in non-OSRD work. Projects ranged in size from the 808-person Radio Research Laboratory, which occupied a whole wing of the biology building, to 454 at the Underwater Sound Laboratory, to a lone researcher working in his own office.[51] The Computation Laboratory was one of Harvard's smallest contracts in terms of personnel; those personnel were drawn into the Navy more or less by serendipity.

Aiken, "a gray-eyed six-foot blond Viking from Wisconsin," had become an assistant professor at Harvard University by mid-1941.[52] The basic design of his computer was complete by then, and the machine was under construction at IBM. Nevertheless, Aiken volunteered for the U.S. Naval Reserve, took up a commission as a lieutenant commander, and went to teach magnetic mine technology in Yorktown, Virginia. While at the Mine Warfare School, Aiken made many trips to Washington, D.C., most probably to advertise his machine and arrange for its use by the Navy. In the meantime, however, he needed someone to act as his deputy on the project and as liaison with IBM.[53] In typically abrupt fashion, Aiken recruited and hired Robert V. D. Campbell on the basis of a brief interview while changing trains at Grand Central Station, New York City, during the Christmas vacation of 1941. Campbell, a graduate student in the Harvard Physics Department, turned out to be an excellent choice. For the next two years, in addition to keeping up with his own academic career, he worked closely with engineers at IBM to bring Aiken's machine to completion. Campbell's main tasks were to check circuit diagrams and to develop programs to test each component of the machine as it was built. There was no precedent for much of what he was doing, nor any training; a notable characteristic of the work performed on the Mark I was its innovation.[54]

In January 1944, with Aiken still stuck in Yorktown, the Mark I was disassembled at IBM's plant at Endicott, transferred to Harvard, and set up in the old battery room in the basement of the Cruft Laboratory by a team of IBM technicians. On one of his trips to Washington Aiken had visited Rear Admiral Van Keuren at NRL in Anacostia, where much of the Navy's research on radar, radio, and sonar was conducted. Later, Aiken had been given a tour of the facility by Richard Bloch, a young Naval Reserve ensign. In 1941, as an undergraduate at Harvard College, Bloch had volunteered for the Navy's V7 program, which committed him to officer training upon graduation. When Aiken found that Bloch was a recent mathematics honors graduate of Harvard, he invited him to return to his alma mater to work at the newly created Computation Lab. It did not take much to persuade Bloch to fulfill the rest of his Navy obligation at Harvard, though how NRL was induced to relinquish him is not known.[55]

Finally, in June 1944, Aiken was promoted to commander and sent to run the BuShips Computation Laboratory at Harvard. It is not clear how Aiken managed to obtain this transfer nor by whom it was authorized. In an interview years later Aiken was to say that one day he received a telephone call at Yorktown from a "high ranking naval officer" who wanted to know why he was not running his calculator. He replied that he was just following orders. Within hours those orders were changed, and Aiken was on his way back to Cambridge to become, as he put it, "the only man in the world who was ever commanding officer of a computer."[56]

Although the Mark I technically belonged to Harvard, during the war its use was devoted exclusively to the military; the Navy paid for its operation, all the salaries, and even an eight-hundred-dollar monthly rent to Harvard. This set the lab apart from the rest of the university; its outside funding led to independence and a certain isolation.[57] When staff members needed medical or dental work, for example, and asked what facility to report to, they were told, "Go anywhere."[58] Tucked away in a basement surrounded by ivory towers, Aiken's Computation Lab was guarded night and day by Navy armed guards.

Aiken's little staff grew quickly, however, and by the August 1944 dedication there was a full Navy crew in place. When Dick Bloch had moved up from the NRL in March, Aiken had indicated to him that he should help get the machine operational as soon as possible. Bloch had never taken an engineering course and had to teach himself on the job. In addition, his particular assignment was to learn how to develop sets of operational instructions for the Mark I to execute.[59]

On 2 July 1944, after hunting around the campus for several hours, Lieutenant (j.g.) Grace Murray Hopper, USNR, WR (Women's Reserve), finally located the Computation Lab. With a Ph.D. in mathematics from Yale University, Hopper had taught at Vassar College and at Barnard before joining the Naval Reserve in 1943 at the age of thirty-seven. She was motivated by a strong patriotism, and because her great-grandfather had been a rear admiral, she later said, she "naturally . . . went Navy."[60] After graduating first in her class at the Northampton Midshipmen's School in June 1944, Hopper had been sent directly to the BuShips Computation Project.[61] Twenty-one-year-old Ensign Ruth A. Brendel arrived at the laboratory soon after. She had been an instructor in mathematics at the University of Buffalo and had joined the Navy because she thought her technical skills could make a contribution to the war effort.[62] The Navy sent both women to Harvard in answer to a direct request from the Computation Lab for WAVES (Navy women) for scientific billets.[63] It was certainly Hopper's mathematics background rather than any familiarity with computers that instigated her assignment. Thirty years later, asked how she became interested in computing, Hopper replied that she had had no choice in the matter: "I was ordered to the first computer in the United States by the United States Navy, and I reported to the Mark I computer."[64]

Until June 1944, just before Hopper arrived at the lab, Bob Campbell had been Aiken's deputy. Campbell then joined the Navy too and became an ensign, junior even to the young Dick Bloch. Though Campbell believes Aiken probably always preferred that he join the Navy, he had not pressured him to do so; still, Campbell thought the idea rather intriguing, so he signed on.[65] Rank was generally not an issue at the lab; the commander ran a tight operation as far as computing went, but Aiken was interested in performance, not hierarchy. Those present in the early days, like Campbell, remember that "even though it was a Navy organization[,] . . . Aiken didn't stand on ceremony very much, and it was quite informal."[66] As one petty officer recalls, "Personal relations were atypical for a Navy unit."[67]

The Navy provided enlisted men as well as officers to work at the lab. One report states that a number of the former were IBM technicians who, while working on the Mark I at Endicott, had been "drafted en masse into the Navy while still assigned to the computer project."[68] Delo A. Calvin's account questions this. In February 1944, Calvin, a customer engineer for IBM in Florida, was inducted into the Naval Reserve. In July, he was sent to Harvard. He and three other petty officers who had had three or four years' experience repairing IBM equipment were given the rating of "Specialist-I" (for IBM) and were assigned to the Mark I as machine operators. They installed the coded program tape, installed or changed the functional tapes, changed the specified values, set switches, and physically controlled the machine's operation. Another petty officer, John Hourihan, came not from IBM training but via the Navy's Class A Electrician's Mate School. He believes he was selected through the Bureau of Personnel based on requirements set up by Aiken. Today, the Specialists-I would be known as data processors (DPs) and data systems technicians (DSs).[69]

Years later, when asked whom she enjoyed most of the many brilliant people she had worked for in her long career, Grace Hopper chose Howard Aiken. He "always said you could make any mistake in the world once as long as you didn't make it twice," she recalled.[70] Hopper thought Aiken an "excellent leader" who kept the group moving forward at a formidable pace while maintaining high standards, both teaching and challenging his young staff. Even those devoted to Aiken, like Dick Bloch, however, describe him as a "tough hombre"; at times he would bring Ruth Brendel nearly to tears.[71] Bob Hawkins, a technician who worked for Aiken for over ten years, "got along with him fine" but nevertheless added that "he was a hard man."[72]

Everyone worked compulsively long hours at the lab (though theoretically it operated in three shifts), personnel and machine pushing to the limit to help end the war by winning it. Cooped up listening to Bessie's constant clicking (some thought the machine sounded like a giant sewing machine), the staff formed a close fraternity, relieving the pressure by "great kidding around."[73] Aiken, "a superb mentor," was constantly attentive, in his office at all hours with the door open and his back to the machine; if it stopped he was out in a flash to see what was wrong, quickly pitching in wherever necessary to help get it producing numbers again.[74]

Produce numbers it did. Dick Bloch wrote that Bob Campbell "was really responsible for getting the machine into productive operation," but Campbell called Bloch "the primary force as far as I'm concerned."[75] Bloch became so skilled at programming that Grace Hopper used to call him the "Mozart of compnters—the only person who could write a program, flawlessly, in ink."[76] When problems were brought to the Computation Lab, even by other mathematicians, they had to be prepared for the machine using a codebook put together by Aiken and Campbell that covered every known type of mathematical problem. Once a function was coded in paper-tape form, the tape was preserved so that it could be used again. Gradually, a tape library was assembled, which greatly speeded the work of the programmers. Eventually, the operator, usually one of the enlisted men, would punch the appropriate code holes in the paper tape to feed the problem to the machine.[77] Thus began the concept of programming, central to Aiken's understanding of computing.

At that time Hopper was only the number-three coder (programmer), yet she was busy computing, in three dimensions, the extent of influence of an antimine dipole when Aiken put her to work (against her wishes) writing a manual. Handicapped by her lack of engineering background, Hopper took copious notes from Dick Bloch at the lab or over late dinner at the Coach Grill in Harvard Square. She had to understand all the basic circuits of the Mark I so that she could explain its coding procedures and the plugging instructions. Despite Hopper's success, Aiken, ever practical, was convinced that an engineering education was the most useful for the new field of computing. When a scientist from the Aberdeen Proving Ground visited the Computation Lab in March 1945, Aiken impressed upon him very forcefully "that . . . [he should seek] not mathematicians but engineers" for his Ballistics Research Laboratory.[78] Ultimately, Hopper did a formidable compilation job, putting together a 561-page manual that became the first in a series of thirty-five volumes: the *Annals of the Computation Laboratory of Harvard University*. Published over the next sixteen years and consisting of detailed technical notes and mathematical results of the lab's operations, the *Annals* represent the core of Aiken's contribution to computing, and an impressive legacy.[79]

The Computation Lab completed twenty-three reports for BuShips in less than two years. By 1 January 1946, when the project was transferred to the Bureau of Ordnance, the staff had grown to almost forty. Most of the reports were purely technical, often in the form of laboratory records, and many did not even mention the practical use to which the computations would be put. The projects were so secret that even the coders usually identified them only by letters of the alphabet. During the war BuShips had the final word on the use of the Mark I, and even the Applied Mathematics Panel had to request permission to assign specific problems to it. The machine was much more powerful than anything else then available to the Navy and the nation, so it ran calculations regarded as essential to the war effort.[80]

One of the first problems the lab received from the Navy concerned fire control calculations for five-inch, 38-caliber antiaircraft guns. The completed solution accommodated input variables including target bearing, elevation, and range, the ship's angle of pitch and roll, drift angle, time of flight, and residual projectile velocity. High-capacity projectiles had been developed so much faster than the corresponding range tables that in 1942 the Navy was already some five hundred tables behind. The advent of proximity fuses also meant extensive recomputation of existing tables. Until the Mark I became operational, the Navy had to rely on "acres of girls . . . using hand-driven calculators" to create such tables.[81]

Another early problem run for BuShips involved solving ten simultaneous algebraic equations for a multiple correlation. The purpose of the calculation was to determine the tensile strength of steel with varying quantities of minuscule impurities, and the results affected the many uses to which steel was put during the war.[82] The Mark I also worked on the theory of coupled antennas, evaluated the accuracy of experimental fire control computers designed and built by NRL, ran numbers for the MIT Radiation Lab that could not be handled by MIT's own differential analyzer, and calculated the effective ranges of magnetic and acoustic mines.[83]

By October 1944, Aiken's lab was undertaking computations for the Bureau of Ordnance (BuOrd) on spherically and cylindrically symmetric underwater blast problems. The problems, dealing with the pressure increases that occur in convergent detonations, were carried out in conjunction with Dr. J. Schilt's computing section at Columbia University. The work was overseen by AMP, to whom regular reports were submitted. At first it had been thought possible to carry out all the computations on Columbia's IBM punched-card equipment, but the volume of material produced was too extensive.[84] A numerical computing scheme was therefore set up that seemed "suited for the Harvard machine. Conferences with Lt. Comdr. Aiken at Cambridge confirmed this," and permission was sought from BuShips to use the Mark I.[85]

Perhaps the largest problem run by Aiken—problem J—was the compilation of tables of Bessel functions, requested by Dr. Bernard Salzberg at NRL. Bessel functions are important in applications as diverse as radio wave propagation, heat flow, and frequency modulation. The production of Bessel tables became a huge project at the Computation Lab, lasting at least five years; it was run whenever there was no problem of higher urgency, especially at night. Dick Bloch did most of the computing for this project. The electric typewriters produced such clear results that the tables could be printed directly, in a photo-offset process; avoiding retyping contributed powerfully to one of Aiken's chief concerns, which was reliability. Eventually Bessel and other functions filled twenty volumes of the *Annals of the Computation Laboratory*.[86] The Computation Lab also computed tables of Hankel functions. These had been requested by NRL but were also used by other naval research activities, such as NOL, the U.S. Navy Radio and Sound Laboratory, and the David Taylor Model Basin, for solution of problems of radio wave propagation and radiation, underwater sound propagation, and the like.[87]

In March 1945, Dr. Philip M. Morse, an MIT physicist who headed the Antisubmarine Warfare Operations Research Group, suggested that the Mark I might be used on tables of Mathieu functions he urgently needed to complete one of his studies.[88] Morse's group had firmly established in the Navy the new field of Operational Research, which had been instrumental in, among other things, the defeat of the German U-boats. Yet during the war there were those who doubted the value of calculations of mathematical tables. Hunter College mathematician Mina Rees, technical aide to AMP, explained that "it is seldom possible to justify in advance the computation of extensive and fundamental tables in terms of military necessity; yet those tables when they have been computed are found to be of wide and important usefulness, both for military and for other research."[89]

In October 1943, the Navy's ballistics center at Dahlgren, Virginia, had expressed interest in Dr. George Stibitz's relay device for computing solutions to the differential equations necessary for ballistics tables. Before committing to having the Bell Telephone Laboratory construct a computer, however, the Navy requested the Applied Mathematics Panel to "conduct a survey of the present possibilities in the field of step-by-step analyzer design and construction to see whether or not an adequate and sufficiently flexible analyzer can be designed and built at this time."[90] The AMP head, Warren Weaver—who had taught Howard Aiken calculus years earlier and who knew of his nearly completed machine at Harvard—directed that it be included in the survey. Very likely, the Navy-initiated survey of computational equipment, and the attention thus focused on the Mark I, combined to spur the Navy's takeover of the

Harvard machine under its creator, Aiken.[91] Moreover, the eventual result of the survey was that Aiken won the Dahlgren contract too, the Navy paying "a quarter of a million dollars for a machine like the Harvard machine" to be constructed.[92]

By the time the Mark I was fully operational, Bob Campbell was already absorbed in helping Aiken design the Mark II for the Navy, and it was Campbell who wrote the original prospectus. Again, Aiken decided to stick with an elecrromechanical device, in the interests of getting reliable results quickly. He believed vacuum tubes were still problematic, but his improved design for the Mark II made it ten times faster than the Mark I.[93] Until the Mark II went into operation at Dahlgren in 1948, the work of computing range tables was done under contract by MIT with a mixture of old and new differential analyzers, IBM equipment, and "a battery of [human] computers."[94]

When in August 1944 the celebrated mathematician John von Neumann from the Institute for Advanced Study at Princeton went to the Computation Lab for calculations he needed, he "didn't know a computer from a tomato basket," quipped Dick Bloch.[95] Grace Hopper confirms this, noting that von Neumann would appear at the lab at intervals, when "he'd go over and peer at the printouts on the typewriters."[96] After the war, von Neumann would do impressive work in computer design, but when he arrived at Harvard the nonlinear partial differential equation he was dealing with had to be made amenable to solution on a finite computer basis. At tbe time, the Navy's mathematicians at Harvard were a rarity—the first programmers. No programming languages existed yet, and von Neumann had to rely on these people, in this case especially on Dick Bloch, for the huge task of programming and sequencing his problem.

By October 1944 von Neumann had reported to AMP that Aiken "has put the problem on and has shown even more direct interest than expected by assigning to it a member of his own staff, Ensign Bloch."[97] In what he describes as "proper Navy tradition," Bloch did not press von Neumann for information about the project, although he knew von Neumann's work on spherical shock waves came from the Los Alamos National Laboratory in New Mexico and, as he correctly assumed, it dealt with atomic fission.[98] Von Neumann was wrestling with the difficult implosion problem for detonating plutonium, which involved lengthy mathematical calculations. The numbers run on the Mark I were necessary to complete his work, which resulted in the plutonium bomb that exploded at Alamogordo, New Mexico, on 16 July 1945—the first atomic detonation—and the "Fat Man" device dropped on Nagasaki, Japan, on 9 August 1945.[99] This was certainly the most dramatic example of the part played by the Mark I in the war effort.

By November 1944, after only six months of operating the Mark I for the Navy, Aiken was already writing that "we are at present so much occupied with the problems submitted to us in connection with the war effort that we cannot take the time to publish a suitable scientific article dealing with the calculator."[100] It sometimes seemed as if Aiken lived at the lab. He would often go home late in the evening, only to reappear after three or four hours of sleep. All he wanted was to see results coming out of the machine: "Are we making numbers, are we making numbers?" was his constant wartime refrain.[101]

The electronic ENIAC produced no numbers for the war effort. Intended to fill the Army's pressing computation needs, the ENIAC was developed at the Moore School by John Mauchly and a brilliant young engineering graduate student, J. Presper Eckert. In spite of erroneous statements to the contrary in popular works on the history of computing, the ENIAC did not produce usable results until 1946. Until then it was not even clear that vacuum tubes could be used effectively in computers.[102] In July 1945, Captain Herman Goldstine, a University of Chicago mathematician serving as Army liaison with the Moore School, had asked the Chief of Ordnance for any reports issued by Aiken on the Navy's Harvard IBM machine. "I feel it would be a great help to us," Goldstine wrote, "if we could see the methods that he used to handle this problem."[103] By then the Mark I had already been operating for a year.

Why then has the ENIAC won the battle for historic recognition? How could the *Wall Street Journal* publish articles about the first programmers in the United States that completely ignored the Mark I, and without arousing protest? The pervasiveness of the myth that the ENIAC was the first real—because electronic—computer has been allowed to obscure the Mark I. This is partly because some have considered the Mark I "a technological dead end."[104] They ignore one of Aiken's most important contributions: the Mark I's punched-tape programming system (the predecessor of today's software) was the first step toward fully automatic program execution, and it was much more like systems now in use than anything in the ENIAC or its contemporaries. The Mark I coders created what were essentially the earliest digital computer programs: stored programs—including subroutines—independent of the machine itself, in this case on paper tape and in programmers' notebooks. By contrast, the ENIAC, designed for a specific task and not conceived as a universal machine, had an unwieldy programming system of external plugs, which could take a day or more to set.[105]

A biographer of Thomas Watson—possibly biased—has described the Mark I as "a lumbering giant of primitivism and obsolescence" and claims that it was "of little value."[106] Yet during the war the only functioning alternatives to the Mark I were analog machines like Bush's differential analyzer, and manual calculators. Douglas R. Hartree, a British professor of mathematical physics who was an authority on computers and very familiar with both the Mark I and the ENIAC, has elegantly disposed of the idea of competition between them. He regarded each, he wrote in 1949, "as being outstanding steps in the development of automatic general-purpose machines, the one as the first practical realization of such a machine and the other as the first electronic digital machine."[107]

In 1946, Aiken, discharged from the Navy, resumed his academic career at Harvard as full professor and Director of the Computation Lab. Each of his staff reverted to civilian status and left the lab, which now became a civilian organization for the first time since the Mark I had taken up residence in February 1944.

Even after he completed the electronic Mark III and Mark IV, Aiken found that some of his contemporaries still viewed him as a conservative, especially after he abandoned machine design altogether in favor of program development, which seemed of only peripheral significance. A more persuasive argument has been made by Grace Hopper, among others well qualified to judge, that Aiken was actually ahead of his time in recognizing the importance of software. This seems to have been largely forgotten, as have Aiken's many other postwar contributions to the new field in applied science: the science of computing.[108] Aiken understood the need to program the quickly growing number of computers, and at Harvard he introduced what may have been the first academic courses in computer science, a decade before such courses existed in most universities. He also organized successful international conferences to encourage open discussion of computers and computing.[109] In fact, what has caused the eclipse of Aiken and his Mark I has not been lack of merit but lack of champions. These should have been found at Harvard and in the Navy.

None of Aiken's little band of scientists remained at Harvard for long after the war. Though some of them went on to lifelong careers in the field to which Aiken had introduced them, making contributions that reflected his inspiration and rigorous training, they did not stay to form a solid phalanx of scholarship that might have buttressed Aiken's reputation within university circles. Both Bob Campbell and Dick Bloch entered the world of industry, at first helping Raytheon to establish its computer project, which at one point was staffed almost completely by Harvard Computation Lab alumni. Grace Hopper stayed on at the lab as a research fellow under Navy contract, working on the Mark II and then on the electronic Mark III. She wanted to join the regular Navy when women were admitted in 1948, but she was two years over the cutoff age of thirty-eight. In 1949, Hopper joined the Eckert Mauchly Computer Corporation and worked on the UNIVAC I, the first commercial computer.[110] Looking back in 1982, Grace Hopper underscored the significance of the Mark I. "Remember," she pointed out, "there weren't more than about ten computers in the whole world at that time." There had been no associations to learn from, no periodicals, "no nothing. It was a new industry."[111]

At the end of World War II, Admiral Furer wrote to Vannevar Bush, noting the fact "that the scientist and the Navy would find themselves so adaptable to each other's way of doing business was unexpected by many."[112] That may have been—and in some quarters may still be—conventional wisdom. But the cooperation would not have surprised Howard Aiken, who moved so easily in both worlds.[113]

Notes

1. "John Harvard's Journal," *Harvard Magazine* (September–October 1997), p. 68.

2. "Harvard Receives $15 Million to Benefit Computer Science, Electrical Engineering," *Harvard University Gazette*, 31 October 1996, pp. 1, 6.

3. H. H. Aiken, "Proposed Automatic Calculating Machine," ed. and preface by A. C. Oettinger and T. C. Bartee, *IEEE Spectrum*, August 1964, pp. 62–9; I. Bernard Cohen, "Babbage and Aiken: With Notes on Henry Babbage's Gift to Harvard, and to Other Institutions, of a Portion of His Father's Difference Engine," *Annals of the History of Computing*, vol. 10, no. 3 (1988), pp. 175–7.

4. "Robot Brain at Harvard Hot News Copy," *Boston News Week*, n.d., clipping from IBM Archives, Somers, N.Y.

5. Howard H. Aiken and Grace M. Hopper, "The Automatic Sequence Controlled Calculator—1," reprint from *Electrical Engineering*, August–September 1946, I, folder 2, box 1, Grace Murray Hopper Collection 1944–1965, Hopper Papers, Smithsonian Institution, Washington, D.C. [hereafter Smithsonian].

6. "Biography of Howard Hathaway Aiken," one printed sheet, n.d., IBM Archives. Documentary and particularly administrative sources for the Computation Lab are scarce and scattered. I have found no major collection like those for the MIT Radiation Laboratory or for Harvard's other wartime research labs, for instance the Underwater Sound Laboratory and the Radio Research Laboratory. Published sources on the Mark I are most extensive in works on computer science and on IBM. In general, these sources present the same set of basic, mostly technical facts and little else.

A classic work is Douglas R. Hartree, *Calculating Instruments and Machines* (Urbana: Univ. of Illinois Press, 1949). See also: James W. Cortada, *Before the Computer: IBM, NCR, Burroughs, and Remington Rand and the Industry They Created, 1865–1956* (Princeton, N.J.: Princeton Univ. Press, 1993); Herman H. Goldstine, *The Computer: From Pascal to von Neumann* (Ormond Beach, Fla.: Camelot 1996); Charles J. Bashe, Lyle R. Johnson, John H. Palmer, and Emerson W. Pugh, *IBM's Early Computers* (Cambridge, Mass.: MIT Press, 1986); Emerson W. Pugh, *Memories That Shaped an Industry: Decisions Leading to IBM System/360* (Cambridge, Mass.: MIT Press, 1984); and William Belden and Marva R. Belden, *The Lengthening Shadow: The Life of Thomas J. Watson* (Boston: Little, Brown, 1962).

7. I. Bernard Cohen, Harvard professor emeritus of the history of science, has drawn attention to the Harvard factor in articles like "Howard Aiken and the Beginnings of Computer Science," *CWI Quarterly (Centrum voor Wiskunde en Informatica)*, vol. 3, no. 4 (1990), pp. 303–4.

8. Thomas Petzinger, Jr. "History of Software Begins with Work of Some Brainy Women," *Wall Street Journal*, 15 November 1996, p. B1, and "Female Pioneers Fostered Practicality in Computer Industry," *Wall Street Journal*, 22 November 1996, p. B1.

9. A 1973 legal decision in a patent dispute found John Atanasoff's ABC machine, and not the ENIAC, to be the first electronic computer. Documents in the case are in the Sperry Univac Records, Accession 1825 (Sperry Acc. 1825), The Hagley Museum and Library, Greenville, Delaware [hereafter Hagley].

10. Brian Levy, "The Computer," *Newsweek*, special millennium edition, Winter 1997–1998, pp. 28–30.

11. "Aiken, Howard," in Anthony Ralston, ed., *Encyclopedia of Computer Science and Engineering* (New York: Van Nostrand Reinhold, 1983), p. 40.

12. Quoted from Cohen, "Howard Aiken," p. 303; Gregory Webb Welch, "Computer Scientist Howard Hathaway Aiken: Reactionary or Visionary?" A.B. thesis, Harvard University, 1986, p. 38, Harvard University Archives [hereafter HUA]. Welch, a student of Cohen's, convincingly supports this view of Harvard's attitude toward pure and applied sciences.

13. Irvin Stewart, *Organizing Scientific Research for War* (Boston: Little, Brown, 1948), p. 166.

14. *Harvard Alumni Bulletin*, September 1944, folder 21, box 6, Hopper Papers, Smithsonian.

15. Stewart, *Organizing*, p. 152; and James P. Baxter, *Scientists against Time* (Boston: Little, Brown, 1946), pp. 24–5.

16. "Harvard Gets Huge Calculator," *Boston Daily Globe*, 7 August 1944, folder 9, box 6, Hopper Papers, Smithsonian.

17. "Algebra Machine Spurs Research Calling for Long Calculations," *New York Times*, 7 August 1944, p. 17; James Bryant Conant, foreword to *A Manual of Operation for the Automatic Sequence Controlled Calculator by the Staff of the Computation Laboratory, Annals of the Computation Laboratory of Harvard University*, vol. 1 (Cambridge, Mass.: Harvard Univ. Press, 1946); Robert V. D. Campbell, interview by William Aspray, 22 February

1984, Concord, Mass., pp. 15–9, 21, Charles Babbage Institute [hereafter CBI], The Center for the History of Information Processing, University of Minnesota, Minneapolis; and Richard Bloch, interview by William Aspray, 22 February 1984, Newton, Mass., pp. 17–8, CBI; Pugh, *Memories*, p. 6.

IBM objected to Aiken's being singled out as sole inventor, though terms had not yet been defined and there was no way to distinguish clearly between the contributions of the mathematicians and those of the engineers. This was later resolved with the concept of "systems architects." Today there might be general agreement that Aiken was the architect of the Mark I and more, since he also worked very closely with IBM engineers designing the physical mechanisms. Still, Watson's relationship with Harvard never recovered from the perceived slight, and he bore Aiken a grudge for the rest of his life.

18. Cohen, "Howard Aiken," pp. 308–9; Pugh, *Memories*, p. 6; Gregory W. Welch, "Howard Hathaway Aiken: The Life of a Computer Pioneer," *The Computer Museum Report*, Spring 1985, p. 7.

19. Richard M. Bloch, "Programming the Mark I," unpublished manuscript courtesy of Mr. Bloch, p. 2.

20. "General Purpose Digital Computers," n.d., folder "Bell Telephone Labs," box A-C, UAV 289.2005, Records of the Computation Laboratory [hereafter Aiken Correspondence], 1944, HUA.

21. Letter from H. H. Aiken to Dr. Arnold Lowan, 1 November 1944, folder "(dead) BuOrd," box A-C, UAV 289.2005, Aiken Correspondence, HUA.

22. "IBM Automatic Sequence Controlled Calculator," IBM Corporation, 1945, IBM Archives, p. 5; Hartree, *Calculating Instruments*, pp. 74–9; Goldstine, *The Computer*, pp. 112–3; Aiken and Hopper, "The Automatic Sequence Controlled Calculator—1," pp. 1–4; and Bashe et al., *IBM's Early Computers*, p. 29.

23. George Stibitz, "History of 7.5," n.d. but forwarded with letter of 22 March 1946, folder "Division 7," box 10, Record Group (RG) 227, National Archives, College Park, Md. [hereafter NA2].

24. Contract NObs-14966, folder "BuShips Computing Project," box 6, UAV 885.95.2, World War II Government Contract Records, HUA.

25. James G. Hershberg, *James B. Conant: Harvard to Hiroshima and the Making of the Nuclear Age* (New York: Alfred A. Knopf, 1993), p. 128; and Donald D. Spencer, *Great Men and Women of Computing* (Ormond Beach, Fla.: Camelot, 1996), p. 55.

26. David Zimmerman, *Top Secret Exchange: The Tizard Mission and the Scientific War* (Montreal and Kingston: McGill-Queens Univ. Press, 1996), pp. 130, 134 n. 6, 194; for administrative history of OSRD, Stewart, *Organizing*.

27. Zimmerman, *Top Secret*, p. 136.

28. Memo from Warren Weaver to Dr. Ward F. Davidson, 7 December 1943, folder "Operational Research—Navy," box 4, RG 227, NA2.

29. Vannevar Bush, foreword, in Stewart, *Organizing*, pp. ix–x. The section on liaison with the armed services, pp. 151–67, suggests that the Navy did a better job in this regard than the Army.

30. Goldstine, *The Computer*, p. 134.

31. For example, letter from Mina Rees to Commander H. H. Aiken, 2 January 1945, folder "(dead) BuOrd," box A-C, UAV 289.2005, Aiken Correspondence, HUA; and letter to Captain T. A. Solberg, BuShips, from Warren Weaver, NDRC, 26 June 1944, folder "June 1944–July 1944," box 72, series II, Sperry Acc. 1825, Hagley.

32. Colin Burke, *Information and Secrecy: Vannevar Bush, Ultra, and the Other Memex* (Metuchen, N.J.: Scarecrow, 1994), pp. 290–303; and Cortada, *Before the Computer*, p. 203. For Navy "bombes" built by NCR in Ohio, see R. Elaine Barlett, "Sugar Camp Reunion," *Cryptolog*, Spring 1996, p. 1.

33. See Kathleen Broome Williams, "Women Ashore: The Contribution of WAVES to U.S. Naval Technology in World War II," *The Northern Mariner*, April 1998, pp. 1–20.

34. Stewart, *Organizing*, p. 57; Andrew Hodges, *Alan Turing: The Enigma* (New York: Simon and Schuster, 1983), p. 299; and Zimmerman, *Top Secret*, pp. 195–6.

35. Cortada, *Before the Computer*, pp. 190–1; Bashe et al., *IBM's Early Computers*, p. 22; Grace Murray Hopper, interview by Christopher Evans, ca. 1976, p. 12, CBI.

36. Bashe et al., *IBM's Early Computers*, p. 24; Spencer, *Great Men and Women*, pp. 51, 54.

37. Folder "Bell Telephone Labs," box A-C, 289.2005, Aiken Correspondence, HUA; Hartree, *Calculating Instruments*, p. 80; and Goldstine, *The Computer*, p. 115.

38. Cohen, "Howard Aiken," p. 303; Spencer, *Great Men and Women*, preface; and Goldstine, *The Computer*, p. 156.

39. Hodges, *Turing*, pp. 298–9.

40. Cohen, "Howard Aiken," p. 306; Burke, *Information*, pp. 264–5, 281.

41. See folder "(dead) BuOrd," box A-C, and folder "Visitors 1944 and 1945," box C-I, UAV 289.2005, Aiken Correspondence, HUA for numerous examples; folder 22, box 6, Hopper Papers, Smithsonian.

42. "Bessie" derives from the Bessel functions calculated by the Mark I.

43. "Staff of the Computation Laboratory," *Manual of Operation for the Automatic Sequence Controlled Calculator;* and Burke, *Information*, p. 291.

44. Letter from Associate Director of the Harvard Radio Research Laboratory and Associate Director of the Harvard Underwater Sound Lab to Mr. H. A. Wood and President and Fellows of Harvard College, 22 May 1943, folder "Policies," box 2, UAV 885.95.2, WWII Government Contract Records, HUA.

45. Letter from R. W. Hickham to John C. Baker, 28 August 1942, folder "Personnel," box 2, UAV 885.95.2, WWII Government Contract Records, HUA.

46. *An Administrative History of the Bureau of Ships during World War II* [hereafter BuShips History], World War II Administrative History No. 89, vol. 3 (Washington, D.C.: Naval Historical Center [hereafter NHC], Navy Department Library), p. 127. Among the Sperry Univac and Technitrol papers at the Hagley Museum and Library's extensive collection of documents on the development of the computer industry, there are many examples of draft deferrals for scientists.

47. William Rodgers, *Think: A Biography of the Watsons and IBM* (New York: Stein and Day, 1969), p. 143; Cohen, "Howard Aiken," p. 305.

48. Letter from Captain W. G. Schindler, Officer in Charge, Naval Ordnance Laboratory, to Dr. John Mauchly, 20 June 1944, folder "01891–02549," box 70, series II, Sperry Acc. 1825, Hagley.

49. Cortada, *Before the Computer*, p. 203; and Goldstine, *The Computer*, pp. 130–1.

50. Letter from J. G. Brainerd to Dean Harold Pender, 6 April 1945, folder "03086–03145," box 71, series II, Sperry Acc. 1825, Hagley.

51. "Anonymous Research Contracts and Approximate Number of Employees at 8/31/44," folder "Personnel," box 2, UAV 885.95.2, WWII Government Contract Records, HUA; and Rudolph Elie, Jr., "Harvard's Wonderful Achievements in Late War Are Told," misc. newspaper clipping, 24 May 1946, folder "clippings," box C-I, UAV 289.2005, Aiken Correspondence, HUA.

52. "Harvard Gets Huge Calculator," *Boston Daily Globe*, 7 August 1944, folder 9, box 6, Hopper Papers, Smithsonian.

53. "Biography of Howard Hathaway Aiken," IBM Archives; Welch, "Computer Scientist," pp. 43–4; and Campbell interview, CBI, p. 12.

54. I. Bernard Cohen, new foreword to *A Manual of Operation for the Automatic Sequence Controlled Calculator* (Cambridge, Mass.: MIT Press, 1985), p. xiii; and Campbell interview, CBI, p. 12.

55. Bloch, interview by author, 12 September 1997; and Bloch interview, CBI, p. 5.

56. Cohen, new foreword to *A Manual of Operation*, p. xiii.

57. Welch, "Computer Scientist," p. 47; Contract NObs-14966, folder "BuShips Computing Project," box 6, UAV.885.95.2, WWII Government Contract Records, HUA; and Ruth Brendel Noller, interview by author, 23 December 1996, Sarasota, Fla.

58. Noller, telephone interview by author, 31 January 1998.

59. Bloch, "Programming the Mark I," p. 3; Bloch interview, CBI, p. 29.

60. Captain Grace Hopper, interview by Linda Calvert, 3 September 1982–28 February 1983, Women in Federal Government Oral History Project (WFGOH46), Schlesinger Library, Radcliffe College [hereafter Radcliffe], p. 10.

61. Carmen Lois Mitchell, *The Contribution of Grace Murray Hopper to Computer Science and Computer Education* (Denton: Univ. of North Texas, University Microfilms, 1994), pp. 1–11, 24–37, 50–1, 63–4; and Charlene W. Billings, *Grace Hopper: Navy Admiral and Computer Pioneer* (Hillside, N.J.: Enslow, 1989), pp. 30, 36–8, 47–53, 111, 115.

62. Noller, interview by author, 23 December 1996.

63. BuShips History, vol. 2, pp. 140–2.

64. Hopper interview, CBI, p. 1.

65. Campbell, interview by author, 12 September 1997.

66. Campbell interview, CBI, p. 61.

67. Delo A. Calvin, three-page typewritten memoir in author's possession [hereafter Calvin Memoir], 10 March 1998, p. 2.

68. Rodgers, *Think*, p. 170.

69. Calvin Memoir, pp. 1–2; letter from John M. Hourihan to author, 14 March 1998.

70. Hopper interview, CBI, pp. 20–3.

71. Pugh, *Memories*, 10; Campbell, interview by author, 12 September 1997; and Bloch, interview by author, 12 September 1997 for "tough hombre" remark.

72. Robert Hawkins, interview by William Aspray, 20 February 1984, Barnstable, Mass., CBI, p. 15.

73. Campbell, interview by author, 12 September 1997; and Calvin Memoir, p. 2.

74. Bloch, "Programming the Mark I," p. 59.

75. Bloch, "Programming the Mark I," p. 3; and Campbell, interview, CBI, p. 62.

76. Campbell, interview by author, 12 September 1997.

77. "IBM Automatic Sequence Controlled Calculator," p. 6, IBM Archives.

78. Letter from L. S. Dederick to Warren Weaver, 20 March 1945, folder "Aberdeen Proving Ground," box 5, RG 227, NA2.

79. Ibid., p. 51; Campbell and Bloch, interviewed by author, 12 September 1997; and Hopper interview, WFGOH46, Radcliffe, p. 29.

80. Aiken, preface to the *Manual of Operation*; BuShips History, vol. 4, p. 185.

81. Report No. 7, July 1944, BuShips Computation Project Reports 1944–1945, Naval Research Laboratory, Washington, D.C. [hereafter NRL]; *Annals of the Computation Laboratory of Harvard University*, vol. 26 (1951), p. 5; Hopper interview, CBI, p. 2, for quote.

82. Campbell interview, CBI, p. 22.

83. Reports No. 10, October 1944; No. 8, August 1944; No. 5, June 1944, BuShips Computation Project, NRL.

84. Interim Progress Reports to AMP, 21 August 1944, 23 October 1944, 24 January 1945, folder "Project No. 10—Harvard Univ.," box 13, RG 227, NA2.

85. Interim Report to AMP, 24 June 1944, folder "Project No. 10—Harvard Univ.," box 13, RG 227, NA2.

86. Campbell interview, CBI, p. 23; and Cohen, "Howard Aiken," p. 318.

87. Letter to Chief BuShips from NRL, 3 January 1945, folder "(dead) BuOrd," box A-C, UAV 289.2005, Aiken Correspondence, HUA.

88. Memo from Warren Weaver to Mina Rees, 9 March 1945, folder "Project No. 2," box 4, RG 227, NA2.

89. Letter from Mina Rees to Oswald Veblen, 9 June 1945, folder "War Science," box 19, RG 227, NA2.

90. Memo to members of AMP Executive Committee from Warren Weaver, 27 October 1943, folder "AMP Executive Committee—memos to," box 2, RG 227, NA2.

91. Letter from Warren Weaver to Dr. Henry Shapley, 10 January 1944, and letter from Warren Weaver to Prof. E. L. Chafee, 2 March 1944, folder "Harvard," box 20, RG 227, NA2.

92. AMP, NDRC, diary of Mina Rees, 26 February 1945, folder "AMP Mtgs. 1943–46," box 1, RG 227, NA2.

93. Hartree, *Calculating*, p. 81; Campbell, interview by author, 1 February 1998.

94. AMP, diary of Mina Rees, 6 March 1944, folder "AMP Mtgs. 1943–46," box 1, RG 227, NA2.

95. Bloch, interview by author, 12 September 1997. Bloch expresses high regard for von Neumann's mathematical abilities.

96. Hopper interview, WFGOH46, Radcliffe, p. 12.

97. John von Neumann, Interim Progress Report to AMP, 23 October 1944, folder "Project No. 10—Harvard Univ.," box 13, RG 227, NA2.

98. Bloch, "Programming the Mark I," p. 36.

99. Report No. 11, December 1944, BuShips Computation Project, NRL; letter to Dr. Arnold Lowan from Howard H. Aiken, 1 November 1944, folder "(dead) BuOrd," box A-C, UAV 289.2005, Aiken Correspondence, HUA; letter from Bob Campbell to author, 16 August 1998. Von Neumann also worked on calculations for the hydrogen bomb (Hodges, *Turing*, p. 302).

100. Letter from Howard H. Aiken to Dr. Arnold Lowan, 1 November 1944, folder "(dead) BuOrd" box A-C, UAV. 289.2005, Aiken Correspondence, HUA.

101. Bloch interview, CBI, p. 17.

102. Even Cortada, *Before the Computer*, pp. 203–4, gives the inaccurate date of 1945.

103. Letter from Herman Goldstine to Lieutenant J. J. Power, 6 July 1945, folder "July 1945," box 74, series II, Sperry Acc. 1825, Hagley.

104. Bashe et al., *IBM's Early Computers*, p. 32.

105. Hopper interview, WFGOH46, Radcliffe, pp. 16, 130; Hodges, *Turing*, pp. 301–2.

106. Rodgers, *Think*, p. 174.

107. Hartree, *Calculating Instruments*, preface, p. v.

108. Welch, "Computer Scientist," pp. 3, 94–5; and Hopper interview, CBI, p. 4.

109. Cohen, "Howard Aiken," pp. 320–2; and "Aiken, Howard," in Ralston, ed., *Encyclopedia*, p. 41. See also *Annals of the Computation Laboratory*, vols. 16, 26.

110. Bloch interview, CBI, pp. 19, 58; and Grace Hopper, interview by Philip F. Holmer, 20 July 1979, Sperry Univac Oral History Interviews, Acc. 1825, Hagley, p. 1.

111. Hopper interview, WFGOH46, Radcliffe, pp. 13, 15.

112. Baxter, *Scientists*, p. 25.

113. So, too, did Grace Hopper, and instead of Aiken it is she who has become the symbol of whatever institutional memory the Navy retains of its early ventures in computing.

After World War II, Hopper became a pioneer in the development of computer programming languages like COBOL. She spent the rest of her life adding to what she had first learned as a scientist in uniform serving under Howard Aiken. She also remained a naval reservist, returning to the U.S. Navy in 1966 to develop a tactical data system for nuclear submarines. In 1982, Hopper was at the Naval Data Automation Command Headquarters (NAVDAC) in Washington, D.C. Her mission there, as defined in the NAVDAC organizational manual, read in part: "Survey the state of the art in computer technology on a continuing basis. Review and evaluate the new knowledge from all sources, government and civilian, to determine the applicability of such knowledge to major design and development problems. . . . Provide technical assessments of the possibility of applying new concepts in existing systems" (Hopper interview, WFGOH46, Radcliffe, p. 49). In addition, "Amazing Grace," as her colleagues fondly called her, became the Navy's foremost propagandist for its computer program, serving as NAVDAC's representative to learned societies, industry associations, and technical symposia. When she finally retired as a rear admiral in 1986, Grace Hopper, then seventy-nine, was the oldest active officer in the U.S. Navy. She passed away on 1 January 1992.

In 1987, the Navy named its impressive new computer center in San Diego for Grace Murray Hopper. Eleven years later Harvard tore down its computer center named for Howard Aiken, a caption in the university magazine reading "Aiken Adieu." Mitchell, *Grace Murray Hopper*, pp. 1–11, 24–37, 50–1, 63–4; Billings, *Grace Hopper*, pp. 30, 36–8, 47–53, 110–5; for "Aiken Adieu" see "John Harvard's Journal," *Harvard Magazine*, September–October 1997, p. 68. Today, perhaps unfairly, Hopper's name (borne since 1997 by an *Arleigh Burke*–class destroyer) is much better known than that of Howard Aiken, who died on 14 March 1973 at the age of seventy-three, and it is she, not he, who symbolizes the Navy's early computer scientists.

Ψ